BRITTLE FRACTURE AND STRUCTURAL FAILURE OF THE LIBERTY SHIPS DURING WW-II (A)

The spectacular failures of many welded ships during the early years of World War II created a major engineering emergency. The failures involved the loss of both ships and lives, at a cost to the nation of $50 million. Approximately 5000 welded merchant ships were constructed; of these, over 1000 suffered cracks in varying degrees. Some 190 ships sustained serious fractures. A dozen broke completely in two.

In April 1943 the Secretary of the Navy appointed a "Board to Investigate the Design and Methods of Construction of Welded Steel Merchant Vessels". The Board was faced with national responsibility for making urgent and valid decisions. The need was for practical research concerned primarily with design and fabrication, to obtain quick answers even though the solutions were only partial. This was a national emergency and expense was unimportant.

Acknowledgement: The author would like to acknowledge the cooperation of the American Welding Society in making available the extensive extracts from "The Welding Journal" and the "Welding Research Supplement", as well as the U. S. Coast Guard for the "Reports of Structural Failure."

 Written by Hallock C. Campbell, Director of Research, Arcos Corporation.
Revised 1971 by G. Kardos.

A. First View of the Problem

Photographs and reports on vessels which have broken in two

Date of Failure	Vessel	Circumstances of Failure
15 Jan 1943	S. S. Schenectady	At pier in still water, Portland, Oregon
5 Mar 1943	Thomas Hooker	Heavy weather in North Atlantic
7 Mar 1943	J. L. M. Curry	Very high seas in Greenland Sea
29 Mar 1943	Esso Manhattan	Clear weather in Ambrose Channel
Casualties coming within one year		
24 Nov 1943	John P. Gaines	Clear weather near Aleutian Islands
11 Nov 1943	Valeri Chkalov	Heavy storm in North Pacific
9 Jan 1944	Joseph Smith	Heavy seas in North Atlantic
24 Jan 1944	Samuel Dexter	Bad weather in North Atlantic
4 Mar 1944	Joel R. Poinsett	Rough seas off Labrador

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD
NAVCG 2702

This report includes all available information up to 1 April, 1944 (Date)

DESCRIPTION OF VESSEL

Name	Official No.	Type	M.C. Design
SCHENECTADY	242620	Tank Vessel	T2-SE-A1
Builder		**Builder's Hull No.**	**Date Completed**
Kaiser Co., Inc., Portland, Ore.		#1	31 Dec. 43
Owner		**Operator**	
War Shipping Administration		Deconhill Shipping Company	

EXTENT OF WELDING

Hull all welded
No inner bottom

Yes Side shell seams			Yes Deck seams
Yes Side shell butts	Yes Bottom seams	[ ] Inner bottom seams	Yes Deck butts
Yes Frames to side shell	Yes Bottom butts	[ ] Inner bottom butts	Yes Beams to deck
Yes Bulkheads	Yes Floors to shell	[ ] Floors to inner bottom	Yes Deck to shell

CIRCUMSTANCES SURROUNDING FAILURE

(Attach all available details of ship's loading)

Date of Failure	Time	Ship's Location	
16 Jan., 1943	2230 PWT	Tied up at fitting out pier, Swan Island	
Ship's Speed	**Course**	**Draft Fwd**	**Draft Aft**
0		6'-4"	17'-0"
Sea Condition	**Weather**	**Direction of Waves with Respect to Ship**	
Still water	Clear	No waves	
Wind Force	**Wind Direction**	**Air Temperature**	**Water Temperature**
Light	East wind	26° F	40° F

DESCRIPTION OF FAILURE

(Include sketch of fracture showing starting point and relative location of welds and other structural features)

APPARENT STARTING POINT The fracture started at the juncture of the fashion plate at the aft starboard corner of the bridge superstructure and the sheer strake

GENERAL HISTORY AND DESCRIPTION OF FAILURE, INCLUDING KNOWN CONTRIBUTORY FACTORS:

Without warning and with a report which was heard for at least a mile, the deck and sides of the vessel fractured just aft of the bridge superstructure. The fracture extended almost instanteously to the turn of the bilge port and starboard. The deck side shell, longitudinal bulkheads and bottom girders fractured. Only the bottom plating held. The vessel jack-knifed and the center portion rose so that no water entered the hull. The bow and stern settled into the silt of the river bottom. Sounding taken around the vessel eliminated the alleged possibility of the vessel having grounded amidships due to a drop in water level. A slight earth tremor was alleged to have occurred at the time of the casualty. The steel of the sheer strake was slightly below specification in yield point and ultimate strength. The deck stringer was low in yield point. Both steels were notch sensitive at low temperature, but there is no existing specification for this characteristic. The welds between the fashion plate and the sheer strake and between the sheer strake and stringer plate were found to contain defects.

CLASSIFICATION OF FAILURE: Broke in two

DISPOSITION OF VESSEL

Repaired, lost, etc.

Vessel repaired and put in service.

SIGNED (Name and Title)

See reverse side for loading details.

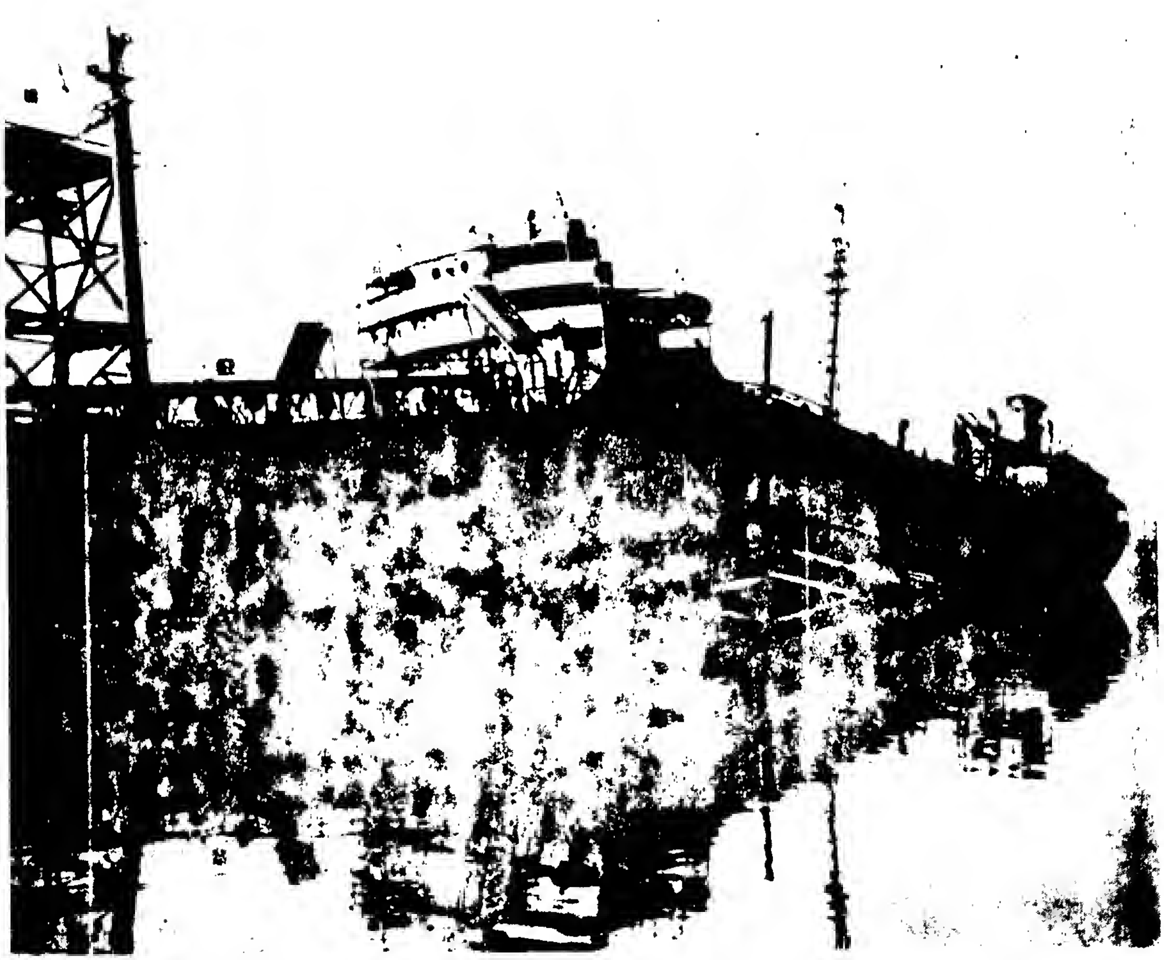
*)A strake is a continuous breadth of hull plating extending from stem to stern of the ship (See fig. 22, page 590 of of the Board of Inquiry Report, Part III)

LOADING AT TIME OF FAILURE

Distribution of Weights

Forepeak	314 Long tons
Cargo tanks	0
F.W. Tanks	71
F.O. Bunkers Fwd.	745
F.O. Bunkers in E.R.	486
I.B. Tank 11-27 P. & S.	73
I.B. Tank 27-44 P. & S.	166
Ammunition Ford.	20
Ammunition Aft	10
Dist.Water Tank	36
F.W. Tank Aft	29
Aft Peak	56
Lightship	5202
Stores & Complement	40
Displacement	7230 Long tons
Corresponding Keel Drafts	7.0' Frd. 15.2' Aft

On the basis of the loading indicated to the left, bending moment calculations were made. The uniform calculated stress in the crown of the deck in still water is 10,700 lbs./in.^{2}



S. S. Schenectady

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD

This report includes all available information up to: 1 Oct. 1944 (Date)

DESCRIPTION OF VESSEL

Name	Official No.	Type (Dry Cargo, Passenger, etc.)	U.C. Design
THOMAS HOOKER	242094	Dry Cargo Vessel	EC2-S-C1

Builder	Builder's Hull No.	Date Completed
New England Shipbuilding Corporation	203	11 Aug., 1942

Owner	Operator
War Shipping Administration	American-West African Line

EXTENT OF WELDING

Yes	Side shell seams					Yes	Deck seams
Yes	Side shell butts	Yes	Bottom seams	Yes	Inner bottom seams	Yes	Deck butts
No	Frames to side shell	Yes	Bottom butts	Yes	Inner bottom butts	Yes	Beams to deck
Yes	Bulkheads	Yes	Floors to shell	Yes	Floors to inner bottom	Yes	Deck to shell

CIRCUMSTANCES SURROUNDING FAILURE
(Attach all available details of ship's loading)

Date of Failure	Time	Ship's Location		
5 March, 1943	2026 GMT	Lat. 64°N., Long. 47°W - Westbound in North Atlantic		

Ship's Speed	Course	Draft Fwd.	Draft Aft
About 9 knots	---	14'	22'

Sea Condition	Weather	Direction of waves with respect to ship
Rough with heavy swells	Heavy	On starboard beam

Wind Force	Wind Direction	Air Temperature	Water Temperature
7	WSW	About 22°	---

DESCRIPTION OF FAILURE
(Include sketch of fracture showing starting point and relative location of welds and other structural features)

Apparent starting point:

Unknown

General history and description of failure:

A loud cracking sound was heard. The upper deck and shell plating on port side abreast of #3 hold were cracked from the bulwark down to tween deck, and from the bulwark to the hatch coaming, including the longitudinal members. A crack from the after starboard side of the hatch coaming extended out to the bulwark and down to tween deck abreast of the dry store room about thirty feet abaft of #3 hold. These cracks were in the center of the plates and not in the welding.
Bending moment in still water = 56,800 Ft. x Tons Hog at #3 Hold
Stress in crown of deck = 6500 Lbs./in.^{2} Tension.

Classification of failure: Cracked deck

DISPOSITION OF VESSEL
(Repaired, lost, etc.)

Vessel was abandoned at 0900 GMT on 6 March, 1943, and when last seen she had a list of 10° to the port side.

Signed (Name and Title)	District

Fig. 1

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD

This report includes all available information up to: 1 Oct., 1944 (Date)

DESCRIPTION OF VESSEL

Name	Official No.	Type (Dry Cargo, Passenger, etc.)	U.C. Design
J. L. M. CURRY	241520	Dry Cargo Vessel	EC2-S-C1

Builder	Builder's Hull No.	Date Completed
Alabama DD & SB Company	231	15 May, 1942

Owner	Operator
War Shipping Administration	Lykes Brothers SS Co., Inc.

EXTENT OF WELDING

Yes	Side shell seams					Yes	Deck seams
Yes	Side shell butts	Yes	Bottom seams	Yes	Inner bottom seams	Yes	Deck butts
No	Frames to side shell	Yes	Bottom butts	Yes	Inner bottom butts	Yes	Beams to deck
Yes	Bulkheads	Yes	Floors to shell	Yes	Floors to inner bottom	Yes	Deck to shell

CIRCUMSTANCES SURROUNDING FAILURE
(Attach all available details of ship's loading)

Date of Failure	Time	Ship's Location
7 March, 1943	1320	Lat. 70°-44' N., Long. 00°-24' E.--Greenland Sea

Ship's Speed	Course	Draft Fwd.	Draft Aft
5 knots	210°	12'-0"	19'-0"

Sea Condition	Weather	Direction of waves with respect to ship
Very high seas	Heavy	----

Wind Force	Wind Direction	Air Temperature	Water Temperature
10 knots	North and West	14°-30°	---

DESCRIPTION OF FAILURE
(Include sketch of fracture showing starting point and relative location of welds and other structural features)

Apparent starting point:

The fractures apparently began from the corners of #3 and #4 hatches in the upper deck.

General history and description of failure:

The vessel came down on a very high sea and split in four places. The upper deck plating, bulwark and side shell fractured on the starboard side from the forward ends of #3 and #4 hatches and on the port side at the after ends of the same hatches. The cracks extended down through the shell plating to below the tween decks. The cracks did not occur along the welds but were clean breaks in the plating, which opened and closed with the working of the ship.
Bending moment in still water = 50,000 Ft. x Tons Hog at #3 Hold
Stress in crown of deck = 5600 Lbs./in.^{2} Tension

Classification of failure: Cracked deck

DISPOSITION OF VESSEL
(Repaired, lost, etc.)

The vessel was abandoned by 1115 on 8 March, 1943, and sunk by shells from an allied vessel.

Signed (Name and Title)	District

Fig 2

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD
NAVCG-3702

This report includes all available information up to 1 April, 1944 (Date)

DESCRIPTION OF VESSEL

NAME: ESSO MANHATTAN	OFFICIAL NO: 242157	TYPE: Tank Vessel	M. C. DESIGN: T2-SE-A1
BUILDER: Sun Shipbuilding & Drydock Company		BUILDER'S HULL NO: # 267	DATE COMPLETED: 22 Aug. 42
OWNER: Standard Oil Co. of New Jersey		OPERATOR: Standard Oil Co. of New Jersey	

EXTENT OF WELDING

Hull all welded
No inner bottom

Yes SIDE SHELL SEAMS		INNER BOTTOM SEAMS	Yes DECK SEAMS
Yes SIDE SHELL BUTTS	Yes BOTTOM SEAMS	INNER BOTTOM BUTTS	Yes DECK BUTTS
Yes FRAMES TO SIDE SHELL	Yes BOTTOM BUTTS	FLOORS TO INNER BOTTOM	Yes BEAMS TO DECK
Yes BULKHEADS	Yes FLOORS TO SHELL		Yes DECK TO SHELL

CIRCUMSTANCES SURROUNDING FAILURE

(Attach all available details of ship's loading)

DATE OF FAILURE: 29 March, 1943	TIME: 1205 EWT	SHIP'S LOCATION: 40 fathoms of water 3/4 mile inshore buoy 3, Ambrose Channel, N.Y.	
SHIP'S SPEED: 14 knots	COURSE: 121° True	DRAFT FWD: 12'-1"	DRAFT AFT: 18'-7"
SEA CONDITION: Slight ground swell	WEATHER: Clear	DIRECTION OF WAVES WITH RESPECT TO SHIP: On port bow	
WIND FORCE: Force 2	WIND DIRECTION: Northeast	AIR TEMPERATURE: 30° to 40°	WATER TEMPERATURE: Not known

DESCRIPTION OF FAILURE

(Include sketch of fracture showing starting point and relative location of welds and other structural features)

APPARENT STARTING POINT: The fracture started in a butt weld between plates A-9 and A-10 at the crown of the deck.

GENERAL HISTORY AND DESCRIPTION OF FAILURE, INCLUDING KNOWN CONTRIBUTORY FACTORS:

With a sound described variously as a thump, thud, bang, crash or explosion, the fracture ran across the deck in way of #6 tank, and down both sides, progressing to the bilge port and starboard. The vessel jack-knifed and the bow dug under an oncoming wave. The crew abandoned in the boats and were picked up by the USCG KIMBALL. The bottom fractured later and the two portions drifted apart. Subsequent examination and tests of the steel in the vicinity of the starting point and from each plate around the periphery of the hull near the fracture indicated that it met existing standards. The chemistry was normal for the class of steel. Impact and notch bend tests showed that much of the steel was sensitive to notches and low temperature. The butt-weld in which the crack started contained oxide, slag and porous areas.

CLASSIFICATION OF FAILURE: Broke in two.

DISPOSITION OF VESSEL

Repaired, lost, etc.

Repaired on drydock at Todd Erie Basin and returned to service.

SIGNED (Name and Title)

See reverse side for loading details.

LOADING AT TIME OF FAILURE

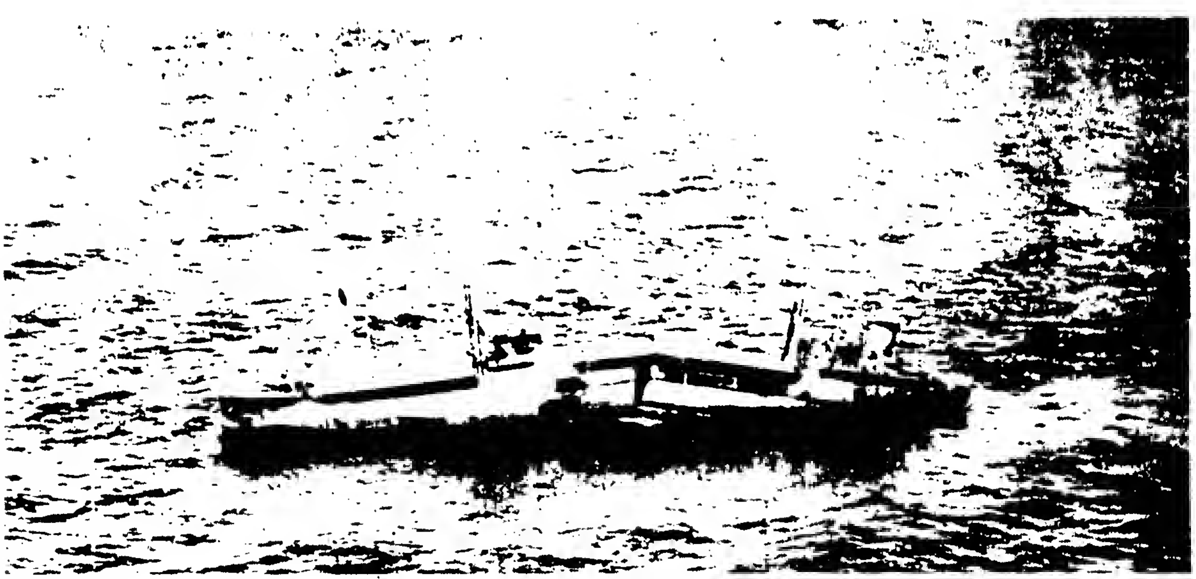
Distribution of Weights

Forepeak		314 Long tons
Cargo Tank #1	P	388
	S	388
#2	P	6
	S	6
	Cl	1385
#3	P	16
	S	16
#4	P	20
	S	20
#9	P	21
	S	21
	Cl	1330
F.W. Tanks		70
F.O. Bunkers		240
F.O. Bunkers		240
I.B. Tank 11-27 P		41
I.B. Tank 27-44 P		82
I.B. Tank 11-27 S		31
I.B. Tank 27-44 S		84
Dist. Water Tank		18
F.W. Tank Aft		29
Aft Peak		56
L.O. Storage		2
Lightship		5455
Stores & Complement		65
Displacement		10344 Long tons

Corresponding Keel Drafts
18'-6-5/8" Aft
12'-1-1/8" Fwd.

At the time of the failure, the tanks were reported to be in the condition shown to the left. This was checked after the two portions had been towed into port. The vessel was taking ballast in accordance with the Navy schedule but due to damaged valves in #7 and #9 tanks which valves were to be repaired on the outbound voyage the schedule was not being strictly followed. The ends of the vessel contained proportionately more ballast. The uniform calculated stress in the crown of the deck in still water and in the condition noted is 12,300 lbs. per sq. inch.

It should be noted that the vessel drafts were otherwise reported to be 15' Fwd. and 22'-8" aft, also 17'-6" Fwd. and 23' aft. It is believed that the calculated drafts (to left) based upon an accurate deadweight determination made in February, 1943 are more nearly correct.



S. S. *Esso Manhattan*

1944 DESIGN OF MERCHANT VESSELS 801

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD
NAVCG-2782

This report includes all available information up to 1 April, 1944 (Date)

DESCRIPTION OF VESSEL

NAME	OFFICIAL NO.	TYPE	M.C. DESIGN
JOHN P. GAINES	243861	Dry Cargo Vessel	EC2-S-C1
BUILDER: Oregon Shipbuilding Corporation		BUILDER'S HULL NO.: # 723	DATE COMPLETED: 8 July 43
OWNER: War Shipping Administration		OPERATOR: Northland Transportation Co., Inc.	

EXTENT OF WELDING

Yes SIDE SHELL SEAMS			Yes DECK SEAMS
Yes SIDE SHELL BUTTS	Yes BOTTOM SEAMS	Yes INNER BOTTOM SEAMS	Yes DECK BUTTS
No FRAMES TO SIDE SHELL	Yes BOTTOM BUTTS	Yes INNER BOTTOM BUTTS	Yes BEAMS TO DECK
Yes BULKHEADS	Yes FLOORS TO SHELL	Yes FLOORS TO INNER BOTTOM	Yes DECK TO SHELL

CIRCUMSTANCES SURROUNDING FAILURE
(Attach all available details of ship's loading)

DATE OF FAILURE	TIME	SHIP'S LOCATION	
24 Nov., 1943	0241 #10 time zone	55-07 N 155-30W 40 miles bearing 175° true from Chirkoff Is.	
SHIP'S SPEED	COURSE	DRAFT FWD	DRAFT AFT
9 knots	Dutch Harbor to Seattle, 76° true	13'-0"	10'-0"
SEA CONDITION	WEATHER	DIRECTION OF WAVES WITH RESPECT TO SHIP	
Long ground swell	Fairly clear	15°-20° off port bow	
WIND FORCE	WIND DIRECTION	AIR TEMPERATURE	WATER TEMPERATURE
5-6 Beaufort	ENE	40°-45° F	About 40° F

DESCRIPTION OF FAILURE
(Include sketch of fracture showing starting point and relative location of welds and other structural features)

APPARENT STARTING POINT: Near Fwd. corners #3 hatch between Frs. #74 and #75.

GENERAL HISTORY AND DESCRIPTION OF FAILURE, INCLUDING KNOWN CONTRIBUTORY FACTORS:

At about 2200 on 23 November, 1943, loud noises were heard but the source could not be located in the dark. At about 0241 on 24 Nov., 1943, an exceptional sea known locally as a "freak" or "sneaker" struck the port bow, curled around the stem, and boarded near the forward gun. The fracture which had apparently commenced during the night immediately propagated. It appears that the vessel broke partially as it passed either over or between swells and the following swell completely broke off the forward end. All crew and passengers were on the after end. Survivors were picked up by U. S. Army Transports except for 10 men, including six soldiers in one lifeboat, which was lost.

CLASSIFICATION OF FAILURE: Broke in two

DISPOSITION OF VESSEL
Repaired, lost, etc.

The bow is believed to have sunk. The stern is aground on Big Koniuji Island.

SIGNED (Name and Title)

See reverse side for loading details.

LOADING AT TIME OF FAILURE

Distribution of Weights

Lightship	3670	Long tons
Crew, passengers & stores	60	
Fuel oil, I.B. #1 Cl	132	
#2 P & S	313	
#3 P & S	232	
#5 P & S	232	
#6	108	
#3 deeps	197	
Settling tanks	83	
Fresh water		
Potable water tank	46	
Reserve feed tank	132	
Forepeak	115	
Aft peak	155	
Lazarette	99	
Salt water ballast		
#1 deep tanks P & S	228	
#2 deep tanks P & S	420	
Hold #4	400	
Hold #5	330	
Cargo Hold #1 Empty drums	81	
#3 Empty & full drums	442	
#4 Empty drums	47	
#5 Empty drums	50	
Displacement	7572	Long tons
Corresponding Keel Drafts	12.15'	Fwd.
	20.17'	Aft

On the basis of the loading shown to the left, indicating the condition at the time of departure from Dutch Harbor, bending moment calculations were made. The uniform calculated stress in the crown of the upper deck when on a standard wave with crest amidships is 15,600 lbs./in.^{2}

S.S. *John P. Gaines*

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD
NAVCG-2782

This report includes all available information up to 1 April, 1944 (Date)

DESCRIPTION OF VESSEL

NAME: VALERY CHKALOV	OFFICIAL NO: None	TYPE: Dry Cargo Vessel	M. C. DESIGN: EC2-S-C1
BUILDER: PermanenteMetals Corporation Richmond Shipyard #2		BUILDER'S HULL NO: #481	DATE COMPLETED: 17 Apr. 43
OWNER: War Shipping Administration		OPERATOR: Union of Soviet Socialist Republics	

EXTENT OF WELDING

Yes SIDE SHELL SEAMS			Yes DECK SEAMS
Yes SIDE SHELL BUTTS	Yes BOTTOM SEAMS	Yes INNER BOTTOM SEAMS	Yes DECK BUTTS
No FRAMES TO SIDE SHELL	Yes BOTTOM BUTTS	Yes INNER BOTTOM BUTTS	Yes BEAMS TO DECK
Yes BULKHEADS	Yes FLOORS TO SHELL	Yes FLOORS TO INNER BOTTOM	Yes DECK TO SHELL

CIRCUMSTANCES SURROUNDING FAILURE

(Attach all available details of ship's loading)

DATE OF FAILURE: 11 Dec., 1943	TIME: 1210	SHIP'S LOCATION: Latitude 35° N, Longitude 168°-25' W	
SHIP'S SPEED: Cut by storm	COURSE: Sovetskaya Cavan Siberia to Akutan Alaska	DRAFT FWD: Not known	DRAFT AFT: Not known
SEA CONDITION: Heavy	WEATHER: Heavy storm, vis. 0	DIRECTION OF WAVES WITH RESPECT TO SHIP: Apparently a head sea	
WIND FORCE: 6 to 8	WIND DIRECTION: Not known	AIR TEMPERATURE: 29° - 34°	WATER TEMPERATURE: Not known

DESCRIPTION OF FAILURE

(Include sketch of fracture showing starting point and relative location of welds and other structural features)

APPARENT STARTING POINT: The cracks which finally broke the vessel started exactly in the forward corners of #3 hatch port and starboard.

GENERAL HISTORY AND DESCRIPTION OF FAILURE, INCLUDING KNOWN CONTRIBUTORY FACTORS:

The vessel departed from Sovetskaya on 1 Dec., 1943, in ballast. Gales and heavy seas were encountered after departure. At noon on 11 Dec., 43, a loud report was heard and three cracks were found, one on the port side at Fr. #74, one on stbd. side at Fr. #74; and one on the stbd. side at Fr. #76. The port side crack extended from the hatch corner across the deck and down the shell to the bilge. The stbd. crack at Fr. #74 was in the side shell from the sheer strake to the tween deck. The stbd. crack at Fr. #76 ran down the side shell from the sheer strake halfway down the tween decks. The vessel was taken in tow by the tug "Joseph Stalin" but at 2206 on 13 Dec. she broke completely in two. Both portions were taken in tow by U. S. Navy tugs and brought to anchorage. The crews did not abandon ship. Ballasting details will be made available by the USSR in the near future.

CLASSIFICATION OF FAILURE: Broke in two

DISPOSITION OF VESSEL

Repaired, lost, etc

Both portions at anchor in Sand Bay, Great Sitkin Island. Future undet.

SIGNED (Name and Title)

S. S. *Valery Chkalov*

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD
NAVCG-2787

This report includes all available information up to 1 Oct., 1944 (Date)

DESCRIPTION OF VESSEL

NAME: JOSEPH SMITH	OFFICIAL NO.: 243693	TYPE (Dry Cargo, Passenger, etc.): Dry Cargo Vessel	M.C. DESIGN: EC2-S-C1
BUILDER: Permanente Metals Corporation #2		BUILDER'S HULL NO.: 119	DATE COMPLETED: 4 June, '43
OWNER: War Shipping Administration		OPERATOR: Alaska Packers Association	

EXTENT OF WELDING

Yes — Side shell seams			Yes — Deck seams
Yes — Side shell butts	Yes — Bottom seams	Yes — Inner bottom seams	Yes — Deck butts
No — Frames to side shell	Yes — Bottom butts	Yes — Inner bottom butts	Yes — Beams to deck
Yes — Bulkheads	Yes — Floors to shell	Yes — Floors to inner bottom	Yes — Deck to shell

CIRCUMSTANCES SURROUNDING FAILURE
(Attach all available details of ship's loading)

DATE OF FAILURE: 9 January, 1944	TIME: 1415	SHIP'S LOCATION: About lat. 44° -30' N., Long. 43° -01' W -- in North Atlantic		
SHIP'S SPEED: 7.2 knots	COURSE: ----		DRAFT FWD: At departure 7'-0"	DRAFT AFT: 21'-0"
SEA CONDITION: Heavy	WEATHER: Very heavy	DIRECTION OF WAVES WITH RESPECT TO SHIP: SW to W cross seas and swell		
WIND FORCE: 6-9	WIND DIRECTION: SW to W	AIR TEMPERATURE: 34°		WATER TEMPERATURE: 50°

DESCRIPTION OF FAILURE
(Include sketch of fracture showing starting point and relative location of welds and other structural features)

APPARENT STARTING POINT

After starboard and forward port corners of #3 hatch fractured in the upper deck.

GENERAL HISTORY AND DESCRIPTION OF FAILURE, INCLUDING KNOWN CONTRIBUTORY FACTORS

At 1400 GCT on 9 January, the vessel was pounding and pitching when she came down heavily with her fore foot causing a fracture in the girder and deck plating at the after starboard corner #3 hatch. At 1600 GCT another fracture occurred in the girder and plating at the forward port corner of #3 hatch. At 0730 GCT on 11 January the third fracture occurred in upper deck plating at the starboard inside after corner of midship deckhouse to entrance of starboard alleyway extending to forward starboard corner of #4 hatch, across the deck to port side, through bulwarks, down side plating to light load line and then turned forward. Longitudinal girders fractured in line with break on upper deck. Tween deck plating cracked similar to that on main deck. All cracks developed across the center of a plate or stiffener and not in welding. Loading data inaccurate - No bending moment computed.

CLASSIFICATION OF FAILURE: Cracked deck

DISPOSITION OF VESSEL
(Repaired, lost, etc.)

The vessel was abandoned at 1430 on 11 January, 1944, and shelled to sinking condition by escort vessel.

SIGNED (Name and Title)	DISTRICT

Fig. 3

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD
NAVCG-2782

This report includes all available information up to: 1 April, 1944 (Date)

DESCRIPTION OF VESSEL

Name	Official No.	Type	M.C. Design
SAMUEL DEXTER (2)	243200	Dry Cargo Vessel	EC-2-S-C1
Builder		**Builder's Hull No.**	**Date Completed**
Delta Shipbuilding Co., Inc.		# 42	15 Apr. 43
Owner		**Operator**	
War Shipping Administration		Waterman Steamship Agency, Ltd.	

EXTENT OF WELDING

Hull all welded

Yes Side shell seams			Yes Deck seams
Yes Side shell butts	Yes Bottom seams	Yes Inner bottom seams	Yes Deck butts
Yes Frames to side shell	Yes Bottom butts	Yes Inner bottom butts	Yes Beams to deck
Yes Bulkheads	Yes Floors to shell	Yes Floors to inner bottom	Yes Deck to shell

CIRCUMSTANCES SURROUNDING FAILURE
(Attach all available details of ship's loading)

Date of Failure	Time	Ship's Location	
21 Jan., 1944	2100	Lat. 54°-48' N; Long. 22°-45' W	
Ship's Speed	**Course**	**Draft Fwd**	**Draft Aft**
Hove to 47 RPM	United Kingdom to New York	9'-8"	21'
Sea Condition	**Weather**	**Direction of Waves with Respect to Ship**	
High seas	Bad weather	3 points on stbd. bow	
Wind Force	**Wind Direction**	**Air Temperature**	**Water Temperature**
8	WSW	40°	48°

DESCRIPTION OF FAILURE
(Include sketch of fracture showing starting point and relative location of welds and other structural features)

Apparent starting point: Forward corners of #3 and #4 hatches port and starboard, all four cracks starting exactly in corner. Aft port corner #3 hatch 3 cracks. Starting point uncertain.

General history and description of failure, including known contributory factors:

At 2100 on 21 Jan., deck cracked opposite #3 hatch and vessel was turned with stern to sea. At 2116 deck cracked at #4 hatch. A thorough examination was made on 22 Jan. and the two cracks from the Ford. corners of #3 hatch were found to extend across the deck and down the side to below the 2nd deck port and starboard. The crack across the deck from the stbd. fwd. corner of #4 ran down the side below the waterline. The top of #3 deep tank in #4 hold was partially cracked. The crack from the port fwd. corner of #4 ran across the deck a distance of 2'. The weather moderated during the 22 to 24 January but a watch was kept on the cracks which were gradually increasing and opened and closed 1" in the seaway. Bad weather was forecast so between 1530 and 1630 on 24 January, the vessel was abandoned.

Classification of failure: Cracked deck.

DISPOSITION OF VESSEL
Repaired, lost, etc.

Vessel drifted ashore on Barra Island of the Hebrides. Future undet.

Signed (Name and Title)

See reverse side for loading details.

LOADING AT TIME OF FAILURE

Distribution of Weights

Lightship	3670 Long tons
Crew, passengers & stores	30
Fuel oil, settling tanks	100
Deep tank #3	613
Fresh water, potable water tank	45
Reserve feed	132
Forepeak	141
Aftpeak	155
Salt water ballast	
Deep tank #2	420
Inner bottom #1	144
#2	559
#3	252
#5	252
#6	118
Ballast in holds #2	250
#3	250
#4	500
#5	500
Displacement	7911 Long tons
Corresponding Keel Drafts	10.51 Ford. 23.05 Aft

On the basis of the loading shown to the left, bending moment calculations were made. The uniform calculated stress in the crown of the upper deck when on a standard wave with crest amidships is 16,700 lbs./in.^{2}

REPORT OF STRUCTURAL FAILURE OF INSPECTED VESSEL
UNITED STATES COAST GUARD
NAVCG-2759

This report includes all available information up to: 1 Oct., 1944 (Date)

DESCRIPTION OF VESSEL

Name	Official No.	Type (Dry Cargo, Passenger, etc.)	M.C. Design
JOEL R. POINSETT	242838	Dry Cargo Vessel	EC2-S-C1
Builder		**Builder's Hull No.**	**Date Completed**
Houston Shipbuilding Corporation		43	28 Feb., '43
Owner		**Operator**	
War Shipping Administration		Standard Fruit & Steamship Company	

EXTENT OF WELDING

Yes — Side shell seams			Yes — Deck seams
Yes — Side shell butts	Yes — Bottom seams	Yes — Inner bottom seams	Yes — Deck butts
No — Frames to side shell	Yes — Bottom butts	Yes — Inner bottom butts	Yes — Beams to deck
Yes — Bulkheads	Yes — Floors to shell	Yes — Floors to inner bottom	Yes — Deck to shell

CIRCUMSTANCES SURROUNDING FAILURE
(Attach all available details of ship's loading)

Date of Failure	Time	Ship's Location	
4 March, 1944	0340	Lat.53°-30' N., Long.56°-30' W., in N. Atlantic	
Ship's Speed	**Course**	**Draft Fwd.**	**Draft Aft**
Approx. 6 knots	West by South	13'-0"	21'-6"
Sea Condition	**Weather**	**Direction of Waves with Respect to Ship**	
Rough	Heavy	3 points on starboard bow	
Wind Force	**Wind Direction**	**Air Temperature**	**Water Temperature**
8 - 12	WNW	20°	40°

DESCRIPTION OF FAILURE
(Include sketch of fracture showing starting point and relative location of welds and other structural features)

Apparent Starting Point

Unknown

General History and Description of Failure, Including Known Contributory Factors.

A loud report, followed by two smaller ones, was heard, the engines were stopped, and a general alarm was given. Immediately afterward, the forward end of the ship separated from the after end and floated away. The vessel parted between frames 82 and 83 on the starboard side and between frames 78 and 79 on the port side. The deck fracture passed between the after end of #3 hatch and the forward end of deck house from starboard side to inboard side of strake C-10 where the fracture ran longitudinally forward to frames 78-79 and went outboard on the port side.

Bending moment in still water = 68,900 Ft. x Tons Hog at #3 Hold.

Stress in crown of deck = 6,900 Lbs./in.^{2} Tension.

Classification of Failure: Broke in two

DISPOSITION OF VESSEL
(Repaired, lost, etc.)

Vessel was abandoned at 1600 on 5 March, 1944, with no loss of life. Forward end sank. The after end reached Halifax, N.S., at 0200, on 22 March, by towboat.

Signed (Name and Title)	District

Fig. 4

DESCRIPTIONS OF THE FAILURES

Types of Vessels and Classification of Casualties

A summary of the types of ships represented by the 100 samples examined, and of the number and classification of casualties, ages of ships, and temperatures at failure for the various types of vessels is given in Table 1. The vessels in which failures occurred were of several different types, and had been built at a number of different yards. Hull fractures are classified in accordance with the definitions on page 19 of Reference 1, as class 1 (serious), class 2 (potentially dangerous) and class 3 (minor). Table 1 also shows the number of vessels of each type which broke completely in two or suffered complete fractures of the strength deck or the bottom (both included in class 1 failures). The hull structure was not involved in four of the casualties: A rudder tube and a crack-arrestor strap on Liberty Ships, Type EC2-S-C1, and two mast failures in Victory Ships, Type VC2-S-AP2.

Five of the casualties probably resulted from damage by ice or floating objects three from minor collisions with a tug while docking, two from possible grounding and one from an underwater explosion. The other casualties occurred under normal operating conditions, or in a few cases, during building, alterations or drydocking. Three of the ships were of riveted construction: two Coast Guard Cutters in which plates were cracked while navigating in ice, and a 31-yr-old collier that broke in two during a severe storm.[5] The original hull of another ship was riveted, but the fractures occurred in the welded superstructure during conversion.

Two ships, both T2 tankers, which had suffered separate casualties at different times, and at different locations in the vessels, were counted twice in this investigation. In a few other instances, a sample included material from separate casualties of the same ship. These were considered as a single casualty, and were given the same NBS ship number.* The records indicate that several of the vessels included in this investigation have suffered previous or subsequent casualties, but samples representing these failures were not obtained. Previous failures are not considered in this report except as they might influence the failure under investigation, for example, a failure of, or resulting from, a previous repair.

The age of the welded ships at the time of the casualties ranged from one minute (after launching) to more than 10 years. A few of the cracks occurred during construction, before or after the ship was launched. Most of these vessels were built during the period of World War II, and the majority were less than three years old when the failures occurred. The average age of the Liberty Ships (Type EC2-S-C1) was somewhat less than for most of the other types, probably because of the large number of early failures resulting from structural features that have since been modified. The relatively few riveted ships were 10 to 31 years old.

The temperatures at failure are the air or water temperatures that were reported at the time the failures occurred. Temperatures reported at the time a fracture was found were disregarded unless there was some reasonably definite evidence that the fracture actually occurred at the time, and not previously.

* The "NBS ship number" assigned to each vessel does not correspond to the ship numbers used in some of the references,[1, 4] and is significant only for identification of the samples received and plates tested at this laboratory.

Table 1—Summary of Ship Types, Classification of Casualties, Ages of Ships, and Temperatures at Which Failures Occurred

Type of Vessel	Total Number of Ships Examined	Number and Classification of Casualties						Ages of Ships		°Temperatures at Failure		
		[a]Broke in Two	[a]Deck or Bottom	Class 1	Class 2	Class 3	Other (Note b)	Months Afloat Average	Range	Average °F	Range °F	No. of Ships*
A. Liberty Cargo Ships EC2-S-C1	30	1	2	13	8	7	2	23	0-99	40°	23°-58°	(18)
B. Tankers T2-SE-A1 & A2	27	7	1	19	7	1	-	53	2-96+	46°	30°-67°	(21)
T1-MB-T1	1	1	-	1	-	-	-	41	(1 only)	35°	—	(1)
Tanker, Not MC Type	5	-	1	5	-	-	-	58	9-122+	44°	42°-48°	(3)
Total Tankers	33	8	2	25	7	1	-	54	2-122+	45°	30°-67°	(25)
C. Miscellaneous Types C2-S-E1 and Mod C2	9	-	1	5	4	-	-	63	21-100	43°	27°-60°	(6)
C3-S-A2	5	-	1	3	2	-	-	62	17-110	52°	46°-56°	(3)
Z-ET1-S-C3	5	-	-	3	2	-	-	31	4-75	40°	24°-50°	(3)
VC2-S-AP2	5	-	-	2	1	-	2	57	7-95	35°	20°-54°	(4)
USCGC	3	-	-	-	2	1	-	128	55-207	32°	32°	(3)
Rivetted Collier	1	1	-	1	-	-	-	377	(1 only)	32°	--	(1)
All Other Types	9	-	1	3	3	3	-	73	0-300	17°	0°-60°	(5)
Total Misc. Types	37	1	3	17	14	4	2	74	0-377	35°	0°-60°	(25)
Total All Types	100	10	7	55	29	12	4	52	0-377	40.5°	0°-67°	(68)

a. Number of vessels which broke completely in two or suffered complete failures of deck or bottom strength members, included in Class 1 (serious) casualties.
b. Includes one rudder tube and one crack arrestor strap (EC2-S-C1), and 2 mast failures (VC2-S-AP2).
c. Air or water temperature, depending on location of fracture source above or below waterline.
* Temperature at time failure occurred is not known for some cases, as for example when fracture was found in drydock or after discharge of cargo.

Most of the casualties occurred at low temperatures. The highest temperature at which a fracture is definitely known to have started is 67° F, and the lowest, 0° F. The majority of the fractures started at air or water temperatures between 30 and 45° F, and the few which occurred at higher temperatures generally did not propagate extensively. No relation has been found between the ages of the ships and the failure temperatures, even when ships of the same type were considered. There appears to be no significant difference of failure temperatures for ships of different types.

Origin and Propagation of the Fractures

A ship afloat may be considered as a hollow beam or box girder subjected to complex and variable forces, which are further complicated by stress concentrations resulting from the numerous structural discontinuities that are necessary to the function, operation or construction of the vessel. At sea, the structure may act as a bridge between two wave crests, or as a seesaw balanced on the crest of a single wave. Thus the stresses, especially in the deck and the bottom, may vary in a short time from maximum compression to maximum tension. These dynamic stresses are added (algebraically) to the more or less static stresses such as those resulting from the distribution of the weight of the vessel itself and its cargo, from unequal thermal expansion due to temperature differences, and probably also from residual stresses caused by fabricating operations or accidental damage. The fractures undoubtedly occurred under conditions such that additive tensile stresses, magnified by the effects of stress concentration, exceeded the fracture strength of the steel. Relatively little was known, when these ships were built, about the magnitude of the stresses and stress concentrations existing in welded ships under various operating conditions. Extensive studies in these fields have been conducted during the past decade,[9] and have indicated that stress concentration factors of 2 to 3, and even as high as 4.6 may occur at structural discontinuities.

The weather and sea conditions at the time of the casualties ranged from calm, in port, to heavy storms at sea. From the circumstances reported in some of the cases, it appears that the stresses existing at the time of the casualty must have been almost entirely static. However, in the majority of the failures, dynamic forces resulting from wind and wave action, from inertia loads caused by the pitching of the vessel and from the interaction of elastic waves in the steel could have contributed large and variable components to the stresses existing at the points where the fractures originated.

Stresses resulting from unequal thermal expansion in different parts of the hull structure due to large differences between the air and the water temperature, solar radiation on part of the vessel, refrigerated cargo spaces or heating of the cargo oil may have been contributing factors in several of the failures.[10, 11]

The loading and distribution of the load in the vessel was undoubtedly a factor contributing to some of the casualties, although in several ships in which fractures occurred the calculated average stress in the deck or the bottom was less than 12,000 psi, or roughly one third the yield point of the steel.[1] Fractures originated in the deck area in six of the tankers included in this report (NBS ship Numbers 11, 36, 46, 47, 52 and 61). Five of these ships broke completely in two, two of them while in port in relatively still water. It was noted that in all of those ships the cargo tanks were light. This resulted in a bending moment that caused a tensile stress in the deck as illustrated by the positions assumed by the two parts of the broken tanker shown in Fig. 15. The remaining 26 Class 1 and 2 casualties in tankers (including three ships that broke in two) occurred when the vessels were loaded, and all of these fractures originated in the bottom or bilge strakes, with the exception of one in the forepeak (NBS ship No. 71). The relative bending moments of a loaded tanker and of one that is light may be visualized by comparing Fig. 4 (loaded) and Fig. 15 (light).

The starting points of more than half of the fractures of known origin were in the immediate vicinity of structural features such as hatch corners, ladder cutouts or other openings, or at the abrupt termination of stiffeners such as a bilge keel, longitudinal, doubler plate or parts of the superstructure. The origin of the fractures at these points may be attributed primarily to the stress concentration resulting from a geometrical or structural notch, although in nearly every case the metallurgical effects of welding, flame cutting or mechanical working were also present, and these effects are not separable.

Another third or more of the fractures originated in defective welds, some associated with structural notches, and others in which the only notch present was that resulting from the welding defects. A few fractures started near interlocking welds such as at points where a pad or doubler was welded on top of a seam or butt weld or where two weld beads were laid so close together that a small mechanical notch was formed between the welds. In both of these conditions, the heat affected zones of two welds overlapped or joined. The origin of these fractures probably resulted from the combination of a minor mechanical notch and the metallurgical effects of the successive heating and cooling cycles.

Fig. 2 Piece of ship plate fractured in the laboratory

Fracture source is at intentional arc strike (arrows *A*), similar to fracture sources in a ship as shown in Fig. 12. Arrows *B* and *C* indicate arc strikes with small deposit of weld metal. Note that the fracture source is at the smallest crater. × 1.

Several of the fractures originated at arc strikes or craters formed by striking a welding arc on the plate outside of the weld zone, or near small shallow welds on heavy plate. As some of the features of the arc strikes in the ships were obliterated by the effects of corrosion, an example for illustration was prepared in the laboratory. Intentional arc strikes and small weld beads were made on a piece of ship plate; the piece was cooled in contact with dry ice (CO_2), and broken with a hammer blow while supported as a simple beam. The piece fractured without measurable bending, and the origin of the fracture was at a small arc strike, as shown by arrows *A* in Fig. 2. The appearance of the "fisheye" at the origin of the fracture, immediately under the crater, is similar to those observed in the ship fractures, such as those illustrated in Figs. 11, 12 and 17. A companion piece, tested without arc strikes or welds, withstood several blows and bent without fracture. This experiment demonstrates that an arc strike is an effective notch, and that failures originating at such defects, as observed in the ship failures, may be reproduced in the laboratory.

Figure 3 shows a longitudinal cross section through the arc strike and small deposit of weld metal indicated by arrow *B* in Fig. 2. The difference of the structure of the metal immediately under the crater is an indication of the metallurgical transformations that have occurred. Under the conditions imposed by an arc strike or a small weld, the temperature is raised to the melting point in only a small portion of the total mass. In other

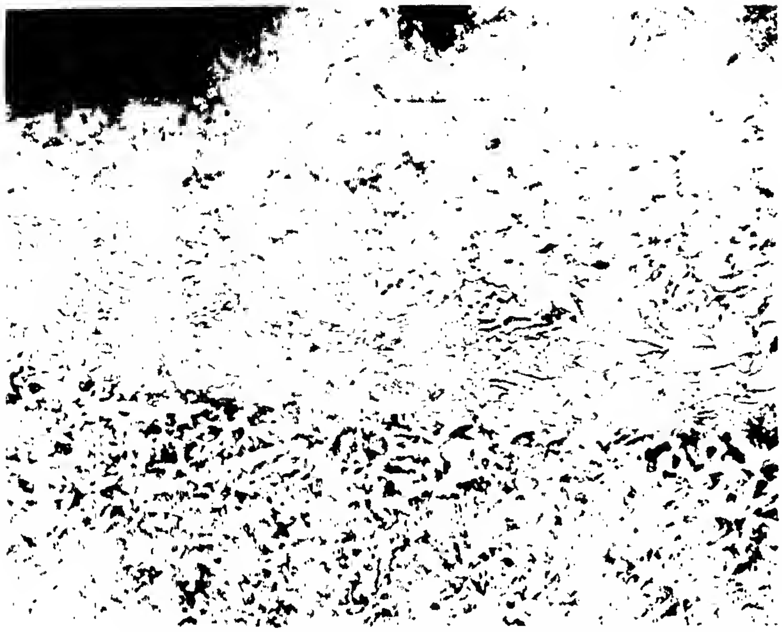


Fig. 3 Cross section through arc strike and weld metal deposit shown by arrow B in Fig. 2

Note the defects and voids in the weld metal (*top*), and the difference of structure of the heated zone (*center*) and the unaffected-base metal (*bottom*). × 75.

words, this heating effect is highly localized, thus the relatively large mass of surrounding metal serves to conduct the heat away very rapidly. This amounts, in effect, to a drastic quench, which causes changes in the metallurgical structure of the base metal in the heated zone, as shown in Fig. 3. The resulting structure is hard and brittle, and in a state of tensile stress caused by restrained thermal contraction and volume changes that accompany the metallurgical transformations. This may lead to the formation of small cracks, but even if cracks are not formed immediately, the condition constitutes a "metallurgical notch" that may be as effective as a mechanical notch in contributing to the origin of a fracture.

Examinations of Fractures and of Welds

Usually the fractured edges of the samples were badly rusted, and some cleaning was necessary before a detailed examination could be made. Loose particles of rust were removed with a stiff bristle brush, and suitable solvents such as acetone or carbon tetrachloride were used to remove the oily residues with which many of the plates were coated. To remove the remaining rust deposits, the fracture edges were soaked and scrubbed with a saturated solution of dibasic ammonium citrate, $(NH_4)_2HC_6H_5O_7$, in warm water. Vigorous scrubbing with a stiff bristle brush (often continued for several hours) was necessary to remove all traces of rust so that satisfactory photographs of the fracture edges could be obtained. This solution does not act as rapidly as some other rust removers, but it does not etch the underlying steel surface to a serious extent. After cleaning, the specimens were rinsed with tap water, sprayed generously with alcohol and dried immediately in an air blast.

The fractures were predominantly of a brittle type, characterized by a break nearly perpendicular to the plate surfaces and a very small reduction of thickness (usually less than 2 or 3%) at the fracture edge. Generally the paint or scale on the plate surfaces was not cracked, even very near to the fracture. This shows that the fractures had propagated with very little plastic deformation of the steel, and that the stress at points a small distance from the fracture must have been lower than the yield point. It is evident therefore that very little energy was absorbed in the propagation of these fractures. In the immediate vicinity of the fracture, however, the sharp notch at the head of the advancing crack caused a stress concentration which exceeded the fracture strength of the materials.

The surfaces of these brittle fractures were rough and usually bore characteristic markings, which have been described as chevrons, herringbones, or arrowheads, as shown in the fracture of the bulwark plate at the right in Fig. 4, and in several of the following photographs. This type of fracture was observed and reproduced at the National Bureau of Standards about 15 years ago, in tests conducted to determine the source of a brittle failure of an aircraft part. These tests, which were discussed in the first NBS report on the examination of steels from a fractured ship,[12] showed that a brittle failure may be produced in a normally ductile metal by applying a tensile stress to a notched-plate specimen. The tests also established the fact that the chevrons point back toward the origin of the fracture.* This made it possible to locate the sources of the fractures in the ships, as for example, in Fig. 4, in which the chevrons point to a faulty butt weld in the bulwark cap rail at the top.

A small percentage of the fractures were of the shear type, having some re-

* An exception to this rule is noted by Kies, *et al*,[9] in that reversed chevrons may be produced by side scratches, which promote initiation of fracture centers near the surfaces, rather than in the center of the plate.

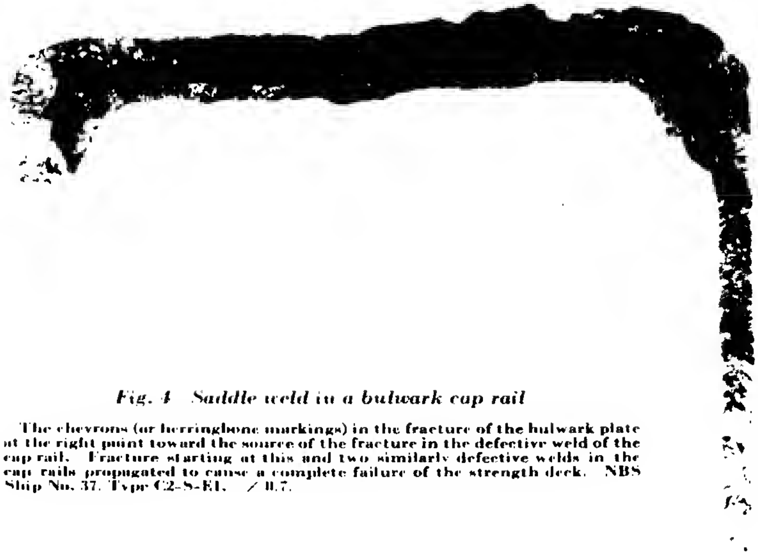


Fig. 4 Saddle weld in a bulwark cap rail

The chevrons (or herringbone markings) in the fracture of the bulwark plate at the right point toward the source of the fracture in the defective weld of the cap rail. Fracture starting at this and two similarly defective welds in the cap rails propagated to cause a complete failure of the strength deck. NBS Ship No. 37. Type C2-S-E1. × 0.7.

duction of thickness near the fracture, and usually showing evidence of ductility by the cracking of the paint and scale for some distance from the fracture. The starting points of the fractures were always of the brittle type, showing no macroscopic evidence of shear, but in several instances brittle fractures changed to the shear type, and in a few of the plates alternating shear and brittle areas were observed. The shear type fractures were generally found in thin plates and were usually associated with the free edge of a plate, the presence of rivet holes or openings, deformation of the plate or the ending of a fracture. Such fractures were not found in plates more than 5/8 in. thick except in one case, a deck plate (NBS plate No. 16c, 13/16 in. thick) which had a shear type fracture intersecting a brittle fracture at nearly a right angle.

Measurements of the thickness reduction at the fracture edge were made when the condition of the sample permitted reasonably accurate determinations. Nearly all of the recent samples were so badly corroded and pitted that accurate measurements could not be made, and many of the other samples did not contain a fracture edge, or the fracture was battered, chipped or welded. The thickness reduction at the brittle fractures ranged from 0.1 to 4%, the higher values generally being associated with plates in which fractures ended. Reductions of more than 5% were found at the shear fractures. Most of the shear fractures were of the single shear type, and the reduction in the actual fracture area was undoubtedly greater than the minimum value determined by measurements at the base of the 45-deg fracture. Thickness reductions of about 30% were found in two small areas of double shear fracture in NBS plate 56B (see Fig. 20).

Many of the fractures classified as brittle type showed narrow zones of shear or shear lips adjacent to the plate surfaces, which probably contributed materially to the total thickness reductions in these cases. For example, on Plate 17C the shear lips were at least 0.02 in. wide (0.04 in. for both sides of the plate). The plate thickness was 0.61 in. and the average thickness reduction was 0.02 in. or 3.4%. If we assume a thickness reduction of 25% in the zones of shear fracture this would account for 0.01 in. or half of the total thickness reduction, and the thickness reduction in the brittle part of the fracture would then be 0.01/0.60, or 1.7%.

Some of the plates were not fractured completely through in a few small areas, giving the appearance of an intermittent fracture, and occasionally cracks several inches long were found on one side of a plate, with no visible indication of a crack on the other side. When these fractures were broken apart for examination, it was found that only a thin skin or shell at the plate surface had not been

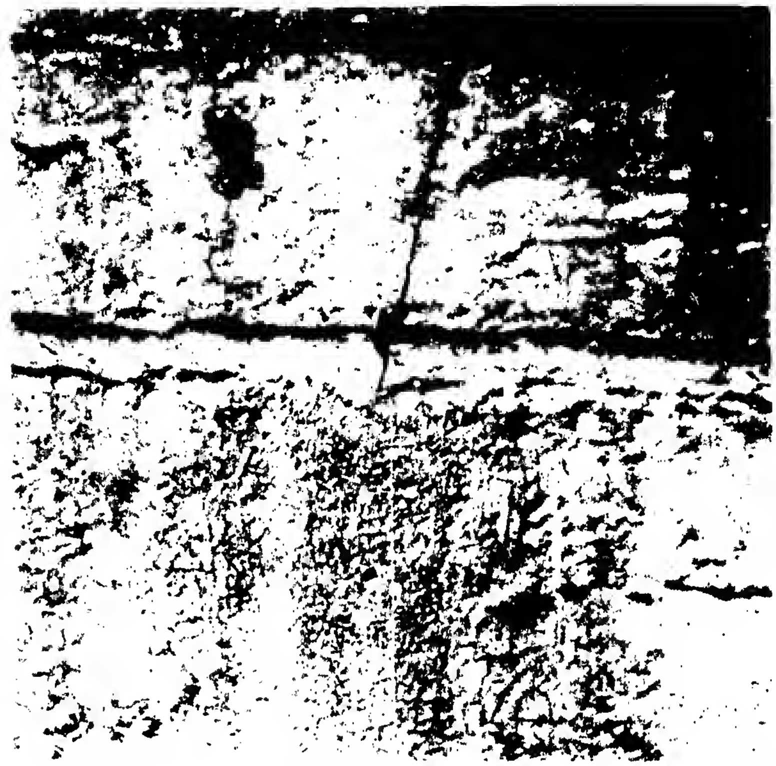


Fig. 5 Strain at the end of a shear fracture shown by cracking of the paint on the inboard side of the plate

A brittle fracture, propagating from above, changed to the shear type in the seam weld, and ended in the lower plate (NBS Plate No. 60A) ½ in. below the weld. In the plate above, the strain adjacent to the brittle fracture was not sufficient to crack the paint. × 0.6 approximately.

fractured, corresponding to the zones of shear fracture observed near the surface in many of the plates which had fractured completely.

The shear lips, and the occasional absence of fracture near the plate surface may be attributed to a combination of two factors: greater notch toughness near the plate surface, especially in rimmed steels, and decreased constraint or biaxial stress near the plate surface.

Figure 5 illustrates the cracking of the paint near the end of a shear fracture, which provides an indication of the strains in the vicinity of a crack. In the seam weld shown in the photograph, the fracture changed from the brittle to the shear type, apparently because of superior properties of the weld metal, and the shear fracture halted in the plate below, less than ½ in. from the seam weld. The cracking of the paint indicates that this plate (NBS plate 60A) was deformed for several inches ahead of the end of the fracture, and for at least an inch on each side of the fracture. Near the brittle fracture in the plate above, however, the paint was not cracked (except for a small area immediately adjacent to the weld, and for the random cracking caused by crazing of the paint film) indicating that the brittle fracture had propagated at a strain less than that required to crack the paint.

A typical end of a brittle fracture in ship plate is shown in Fig. 6. The original crack had rusted, and appears dark in the photograph. The lighter portion at the right was broken in tension in the laboratory. Chevrons, pointing to the left, could be seen in both the old and the new

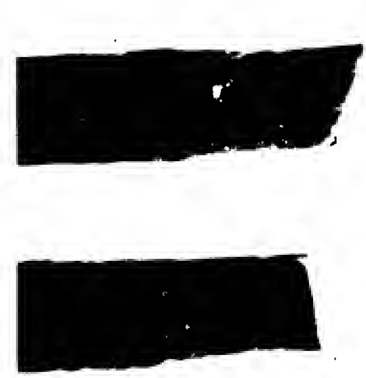


Fig. 6 Typical end of a fracture

The lighter portion at the right was broken in tension in the laboratory. The original crack had progressed farther at the center of the plate than at the plate surfaces. × 1.

portions of the fracture. The original fracture had progressed somewhat farther at the center of the plate than at points nearer to the plate surfaces, resulting in a semicircular or oval shape of the fracture end. Similar oval shapes, of varying symmetry and convexity, were observed at every fracture end which was examined and in every case the fracture was less advanced at points near the plate surfaces. The chevrons were approximately perpendicular to the oval shapes of the fracture ends, suggesting that the chevrons were probably the traces of irregularities in the advancing fracture front. Kies, Sullivan and Irwin[13] have shown that chevron markings may be produced in plastics, and that they may be attributed to level differences of fracture centers which are initiated in the vicinity of the leading edge of the main crack.

It was also noted that the apex angles of the chevrons were not the same in different plates, or even in different parts of the same plate, but the cause of these variations is not definitely known at present. The experiments cited in the previous footnote and in Reference 13 suggest that this phenomenon may be related to differences in the degree of biaxiality in the plate, which would change the concentration of fracture initiation centers. However, it might also be related to the speed of propagation of the fracture, the stress level at various locations along the path of the fracture, the notch sensitivity of the steel or nonhomogeneity of notch sensitivity in the thickness direction.

Semicircular or oval markings, similar to the shape of the end of a fracture, were observed in several of the fractured plates. Often these marks were accompanied by a difference in the degree of corrosion of the fracture edges, a change in the direction of the fracture or a slight indication of shear type fracture, indicating that the crack had stopped temporarily at that point and had progressed further at a later time or under different stress conditions.

The fractures in welds* occurred in regions where the strength of the weld was reduced by subsurface defects which introduced internal notches or which seriously decreased the effective cross-sectional area of the weld, as shown in the butt weld of the bulwark cap rail at the top of Fig. 4. Usually these defects were not visible on the surface, and would not be detectable by ordinary surface inspection methods. In all of the fractured welds that were examined, very evident welding defects were found, such as slag inclusions or porosity, poor fusion, or insufficient weld metal due to inadequate joint preparation or lack of penetration. When the fracture encountered a sound area of the weld, it turned into one of the adjoining plates or, in a few instances stopped. Usually it was not possible to determine the exact starting point or the direction of propagation of a fracture in a weld, as these fractures did not show the herringbone markings or chevrons characteristic of the brittle fractures in plates.

* Fractures parallel to a weld, as distinguished from fractures which propagated across or through a weld from one plate to the next.

Summary and Evaluation of Observations

The lack of ductility and the brittle nature of the majority of the fractures indicated that when the steel was incorporated in the structure of the ship, the mechanism of fracture, or the mechanical behavior of the steel, was not the same as when determined by the usual tensile test, using relatively small specimens. This phenomenon is similar to that observed in tests of notched specimens in tension or bending, particularly at low temperatures. The similarity is also evident in the facts that the fractures in the ships occurred more frequently at the lower operating temperatures, and that the starting points of the fractures could be traced, invariably, to geometrical or metallurgical notches resulting from structural or design details, fabrication processes or defective welds. This phenomenon, called notch sensitivity or notch brittleness, is not peculiar to ship plate alone, and is not confined to metals. The scoring of glass for cutting and the notching of cellophane wrappers are familiar examples in which notch sensitivity is utilized to control the location or direction of a tear or fracture.

The most serious aspect of notch sensitivity, however, is not the fact that fractures may start at structural notches, but that in a notch-sensitive steel a crack, once started, will continue to propagate at a very low energy level. Realization of this fact, together with the observation that in riveted ships the fractures usually stopped at a riveted joint, led to the installation (in vessels already built and in new construction) of riveted straps covering a longitudinal slot in the deck, the bottom plating or the sheer strake, as a preventive measure to limit the propagation of fractures. The effectiveness of these crack arrestors[1, 2] shows quite conclusively that the propagation of the fractures was not a direct result of the loss of the strength and support of the structural members initially fractured, but was due primarily to notch sensitivity. Propagation of fractures was halted by the crack arrestors in nearly every casualty of vessels so equipped, and in the few remaining cases it was reported that the crack arrestors delayed the propagation of the fractures. Thus, even in vessels where almost the entire deck or bottom was fractured, the remaining structure was able to absorb enough energy to prevent the immediate start of a new fracture on the other side of the crack arrestor. However, in the presence of the severe stress concentration caused by the initial crack, the fractures could propagate at relatively low over-all stress and energy levels until the continuity of the metal was broken by the crack arrestor slot.

As stated previously, the more serious casualties in welded ships resulted from the propagation of fractures through or across the welds into adjoining plates. However, in a number of cases far out of proportion to the relative areas of welds and plate metal, the fractures stopped at or near welds which were perpendicular, or nearly perpendicular, to the path of the fracture. In several of the ships, it was noted that fractures appeared to avoid the areas of welds and heat-affected zones but propagated 3 to 6 in. from a butt weld and generally parallel to it. Some of these fractures turned and crossed the weld at a rather sharp angle then turned again and propagated in the adjacent plate parallel to the weld. No instance can be recalled in which a fracture propagated for any distance in the heat-affected zone adjacent to a weld, or continued to propagate in a sound weld after turning from a plate into a weld. This indicates that sound weld metal and the metal in the heat-affected zones adjacent to a weld are not abnormally sensitive to fracture in a direction parallel to the weld.

Fractures of the shear type were relatively more numerous in appendages such as longitudinals, free bulwark plates or corrugated bulkheads than in the shell plates. This (together with the association of shear fractures with thin plate, deformation or buckling, the free edge of a plate or the presence of openings) suggests that shear fractures are more likely to occur in members which are free to deform laterally, and that the brittle fractures are associated with lateral restraint. This constitutes further indirect evidence that the brittle, low-energy fractures are associated with notch sensitivity, since lateral restraint, and restraint in the thickness direction of thicker plates, may impose conditions of biaxial and triaxial stress similar to those which occur at the root of a notch.

However, the failures occurred in vessels of several different types, and at various locations in these vessels, while there were no fractures in the majority of other ships of the same design and construction. It may be that some ships fractured while others did not because the lack of notch toughness of the steel was a borderline deficiency, as, over a period of years, the operating conditions would presumably impose similar combinations of temperature and stress concentration at corresponding locations in all ships of each type. This supposition is supported by the results of the laboratory tests, discussed in Part 2 of this report.

Examples of Typical Failures

It is unfortunate that ship construction

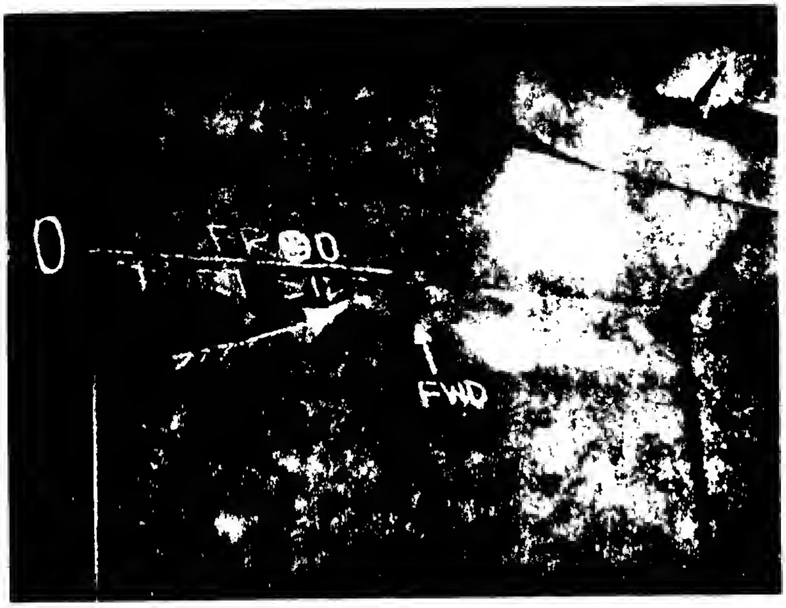


Fig. 7 Fracture originating at a hatch corner of a cargo vessel, NBS Ship No. 32, Type C3-S-12

Fractures originating at both the port and the starboard hatch corners in this ship resulted in a complete failure of the strength deck. Two sister ships had almost identical failures on the starboard side. (U. S. Coast Guard Photograph.)

requires large amounts of welding at points of geometrical discontinuity, as in many cases the welding was blamed for a failure that was primarily a result of stress concentration at a notch created by structural design. Although some fractures originated in defective welds, many started at structural notches in which welding was not the primary contributing factor. Typical examples of fracture sources, some that resulted from welding operations and others in which welds were not directly involved, are shown in Figs. 7 to 19, inclusive.

A fracture originating at a hatch corner is illustrated in Fig. 7. On this ship similar fractures originated in the $1\frac{1}{4}$-in. deck insert plates at both the port and starboard after corners of No. 3 hatch, resulting in a complete failure of the strength deck. The port fracture extended across the deck and into the side plating, and the starboard fracture ended near the edge of the deck, at a bollard that acted as a reinforcement. The hatch beams and coaming, and the deck between the hatch openings, did not fracture except for a few inches near the hatch corners. In two sister ships, NBS ship numbers 70 and 79, almost identical fractures occurred on the starboard side, but in these vessels the port side did not fracture, although small cracks were found at the port hatch corners.

Figure 8 shows a small crack that started at a sharp corner in a ladder opening of a Liberty ship. Similar cracks were found in both the port and the starboard ladder openings of this vessel, and although they had progressed only about 1 in. when discovered, they did form severe notches at critical locations, which might have led to more serious failures. The openings had been made by hand torch cutting, and subsequently dressed by grinding. However, several deep notches still remained on the edge. The fracture, indicated by the arrow, was located at a sharp change in section, which was further aggravated by rough notches resulting from the flame-cutting operation, and probably also by the metallurgical effects resulting from the heating and cooling.

A faulty butt weld in a hatch side facing channel is shown in Fig. 9. Again (as in the weld shown in Fig. 4), the weld metal did not penetrate to the full thickness of the joint—the original flame-cut edge may be seen in the center of the photograph. The upper side of the weld had cracked at some previous time, probably during or shortly after the welding. When the part was painted the crack was covered over, and some paint penetrated the crack, as shown by the light areas near the top of the weld. After this vessel was launched, but before it was completed, there was a sudden complete failure of the strength deck, starting at this joint and at a similar faulty weld on the opposite side.[14] This costly failure might have been averted if, by better supervision and inspection, the initial crack in one side of the weld had been found and repaired before painting.

Fig. 8 Short crack originating at sharp corner in flame-cut edge of ladder opening in sheer strake. NBS Ship No. 9, Type EC2-S-C1. × 1

Fig. 9 Faulty butt weld, showing poor weld penetration, in hatch side facing channel, NBS Ship No. 2, Type L6-S-B1

Dark areas at center are original flame-cut edge of plate. Paint penetration in upper part of weld (light areas) indicates weld was partly cracked before painting. Subsequent failure of weld led to complete fracture of strength deck. × 1.

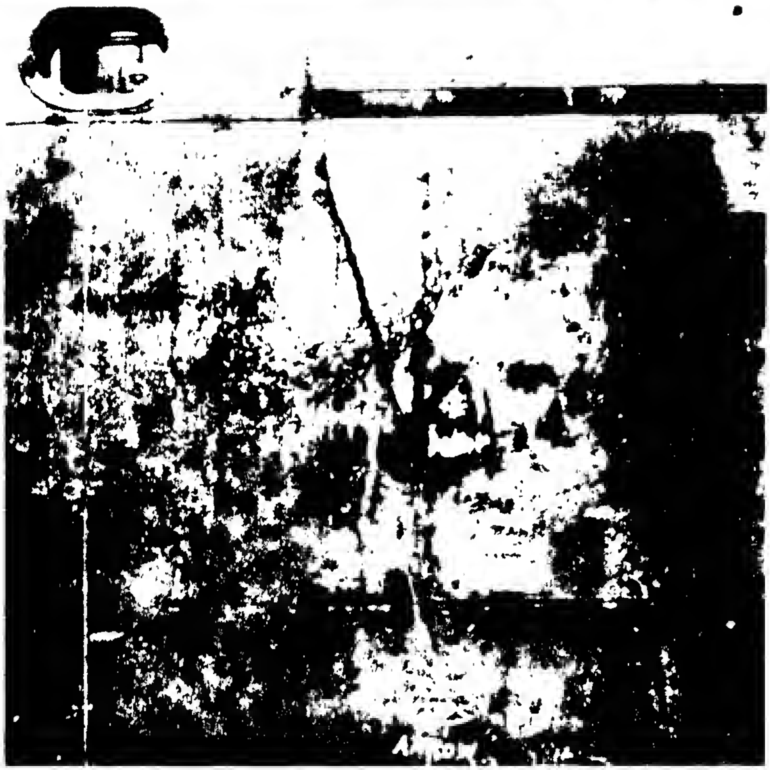


Fig. 10 Fracture source (arrow) at change of section at end of slotted freeing port. NBS Ship No. 21, Type Z-ET1-S-C3. (U. S. Navy Photograph)

Fig. 11 Source of fracture shown in Fig. 10, viewed from inboard and above. Arrow shows arc crater and globule of weld metal on flame-cut edge of sheer strake plate, adjacent to toe of fillet weld

Figures 10 and 11 illustrate another fracture starting at a scupper or cutout above the sheer strake. The source of this fracture (Fig. 11) was at a sharp change in section at the toe of a fillet weld between the sheer strake (below) and the end of a small triangular insert plate (above). A small crater and globule of weld metal (arrow), probably formed by momentary touching of the welding electrode to the plate, was adjacent to the crack. The heat-affected zone under this globule was quite shallow and was about the maximum hardness for this type of steel (Knoop No. 400), indicating very rapid cooling. The edge of the sheer strake plate at this point had been prepared by machine gas cutting. The energy absorption of a notched-bar test specimen taken from a point very close to this edge was only 60% of the average energy absorption at the same temperature (70° F) of similar specimens from the interior of the plate. This indicates that the notch sensitivity of the steel, which was already high, had been increased in the region of the flame-cut edge by the heating and cooling during the cutting operation. The origin of this fracture was attributed to a combination of factors: (1) a notch-sensitive steel, with the notch sensitivity at the edge of the plate further aggravated by heating incident to the flame cutting; (2) low temperature (45° F), which also increased the notch sensitivity; (3) stress concentration at a geometrical notch or sharp change in structural section; (4) a metallurgical notch near the geometrical notch; and (5) rough seas and a strong wind causing unusual stresses in the structure of the ship.

In Fig. 12, the chevrons indicate that there are two fracture sources in the plate near a lap seam weld. These fractures occurred in the shell plating of a Coast Guard Cutter while navigating through an ice pack. Both sources are at small craters where apparently the welder had struck his arc on the plate, away from the area of the weld, and with practically no deposit of weld metal. The origins of these fractures may be attributed to the combination of a metallurgical notch, the small mechanical notch formed by the arc crater, stress concentration resulting from the overlap of the plates, the metallurgical effects of the nearby weld and low temperature.

Fig. 12 Shell plating of Coast Guard Cutter (NBS Ship No. 14) damaged by ice. Chevrons on fractured edge indicate two fracture sources (arrows) at arc strikes on plate, near lap seam weld. × 0.75

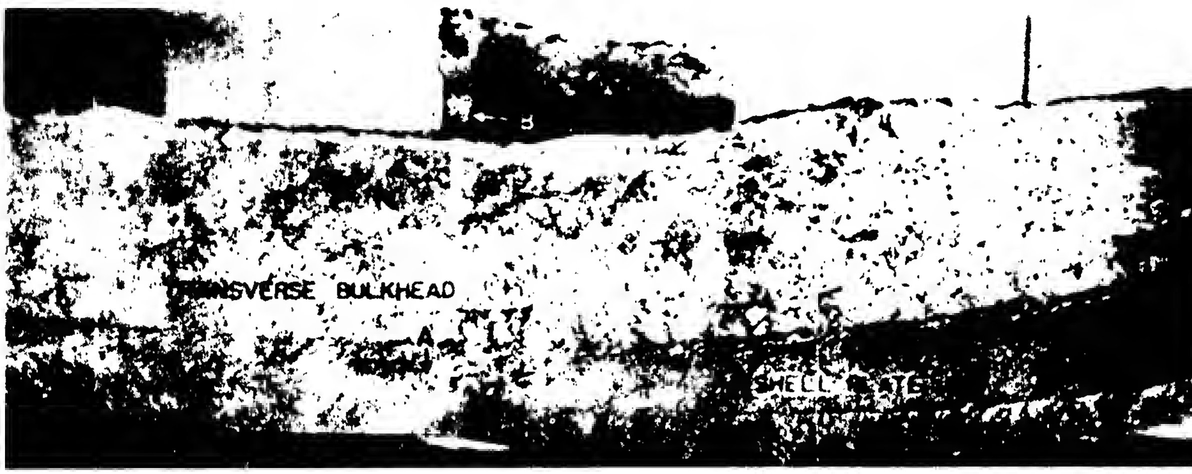


Fig. 13 Source of fracture (arrow A) in shell plating of a tanker that broke in two at sea

NBS Ship No. 8, Type T2-SE-A1. Fracture source is about 2 1/2 in. from transverse bulkhead, exactly at the end of an interrupted longitudinal stiffener. Arrow B indicates the interrupted longitudinal on the other side of the bulkhead.

A fracture in the shell plating of a tanker that broke in two at sea is shown in Fig. 13. The chevrons on the fractured edge clearly indicate the source of the fracture in the shell plate, at the point marked by arrow A. This point, about 2 1/2 in. from a transverse bulkhead was exactly at an end of a longitudinal stiffener. The end of the corresponding longitudinal on the other side of the bulkhead is indicated by arrow B in the photograph. The longitudinals here were interrupted for a space of about 6 in. to allow for insertion of the transverse bulkhead, and were connected to this bulkhead, at a point several inches from the shell plating, by gusset plates on the flanges of the longitudinals, as shown (in another ship) in Fig. 14. The longitudinals were rigidly connected to the shell plating by fillet welds all around. The ends of these longitudinals were not rounded or tapered, but were cut square and perpendicular to the shell plating. This condition constituted a structural notch at the abrupt end of the longitudinal stiffener. Probably the majority of failures in tankers originated at this design detail, which is repeated several hundred times in the structure of a T2 tanker.* Another prolific source of failures was at the end of a bilge keel, which provided a similar geometrical configuration.

Figure 14 shows two overlapping secondary fractures in the side shell of a tanker. Both fractures originated at longitudinal interruptions like that shown in the preceding figure, and there were a number of other secondary fractures starting at similar points. In another tanker (NBS Ship No. 81), nine such cracks were found, each of which had started in the shell adjacent to the end of a longitudinal.

A tanker that broke in two while in port is shown in Fig. 15. The positions assumed by the two parts of the vessel are an indication of the bending moment that contributed to the initiation and propagation of the fracture. Figure 16 shows the area in which the fracture originated, in the starboard deck stringer plate just forward of the chock base near the midship section. The mating edges of the fracture, near the starting point, are shown in Fig. 17. The fracture source was at the toe of a small fillet weld

Fig. 14 Overlapping secondary fractures in side shell of a T2 Tanker, NBS Ship No. 56

Both fractures originated at the ends of interrupted longitudinals near a transverse bulkhead. Triangular gusset plates on the flanges of the longitudinals were torn out of the bulkhead (extreme left). (U. S. Coast Guard Photograph.)

* Several variations of this design detail have been tested in the Mechanics Division of the National Bureau of Standards,[9] to evaluate the effectiveness of practical modifications which have been or may be used in existing ships or in new construction.

joining a clip to the deck stringer plate. The clip (for a wartime countermeasure against mines) was probably attached after the ship was built, and was so placed that the toe of the weld was almost superimposed on the weld at the forward end of the inboard leg of the chock base. At the point of origin of the fracture, between these two welds, there were two small arc craters in the deck plate. (The difficult welding position due to the proximity of the chock base probably contributed to this defect of workmanship.) The craters were partially bridged over with weld metal which was not completely fused to the plate, and which formed the projecting lip on the fracture, visible at the toe of the weld in the lower photograph of Fig. 17.

The origin of this disastrous fracture may be attributed primarily to the arc craters, which aggravated the stress concentration resulting from the stiffening effect of the chock base and from the mechanical notch between the two welds at the end of the chock base. The metallurgical effect of the overlapping heat-affected zones of the two welds, one of which was small and shallow, was probably another contributing factor. The transition temperature of the deck stringer plate, 62° F, was lower than the average values for "fracture through" and "fracture end" plates of comparable thickness (0.99 in.) and was the lowest of all the "fracture source" plates which have been tested. Thus, the plate itself was not abnormally notch sensitive, compared to other ship plates, as measured by the V-notch Charpy test. However, in the vicinity of the welds and the arc craters the notch sensitivity was probably greatly increased, as has been observed in a number of other plates.*

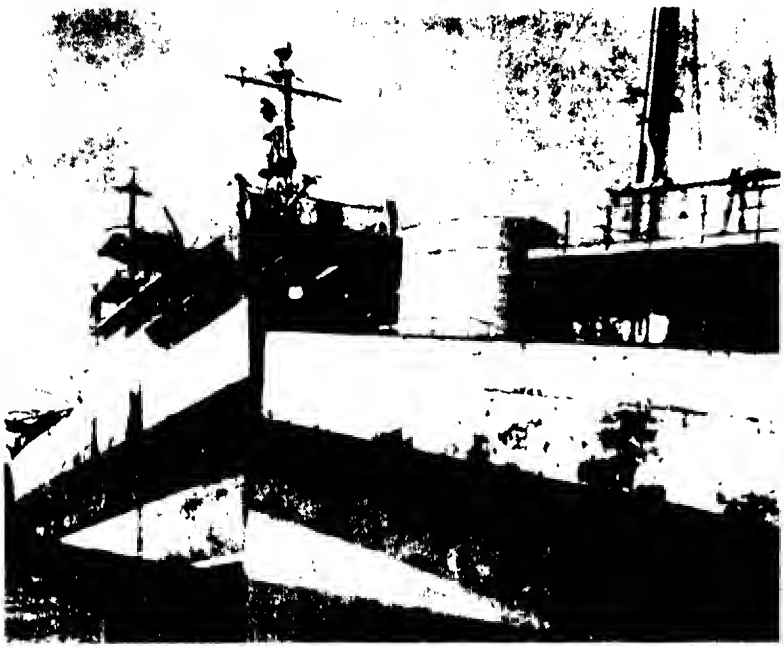


Fig. 15 Tanker that broke in two at dock, viewed from port side, looking forward

The bending moments that contributed to the origin of the fracture are indicated by the positions of the two parts of the vessel. NBS Ship No. 52, Type T2-SE-A2. (U. S. Coast Guard Photograph.)

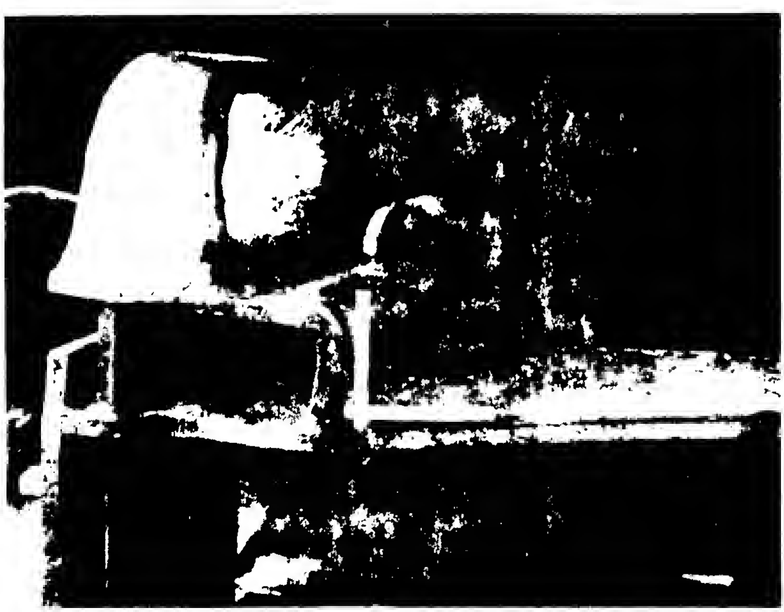


Fig. 16 After edge of fracture in starboard sheer strake and deck stringer of the tanker shown in Fig. 15

The chevrons show that the fracture started in the deck stringer near the inboard leg of the chock base, and propagated into the sheer strake (*left*) and the deck longitudinal and bracket (*lower right*)

Figure 18 shows the region of the starting point of a fracture, in another tanker that broke in two at sea. The origin of the fracture was at an old crack in the top of the half-round scuffing bar which was welded to the top of the sheer strake. The scuffing bar and upper sheer strake had been deformed at some previous time apparently by bumping against a mooring post or the like, and several small cracks (Fig. 19) had been formed in the top of the half-round bar, at a point between two parallel weld beads near the end of a chock base. (This end of the chock base was not perfectly aligned with the top of the sheer strake, and was welded to the half-round, slightly outboard of the weld joining the top of the half-round to the top of the sheer strake.) The heat-affected zones of the two small shallow welds overlapped, but the welds were not joined. The cracks started in the overlapping heat-affected zones, probably as a result of the restraint imposed by the chock base when the deformation occurred. The surfaces of these cracks were badly corroded, indicating that they had existed for some time without further propagation. However, when the ship encountered a critical combination of sea and loading conditions, combined with the factors of stress concentration, low air temperature and resulting increased notch sensitivity, one of these cracks propagated downward through the half-round, then through the lower weld into the sheer strake, and the catastrophic failure resulted. The steel of the half-round (NBS Plate 61A) was inherently more notch

*** It appears significant that in two of the three plates of the fracture source category which had transition temperatures below 70° F, the fractures originated at arc craters. (NBS plate numbers 52A and 21A, see Fig. 11.)**

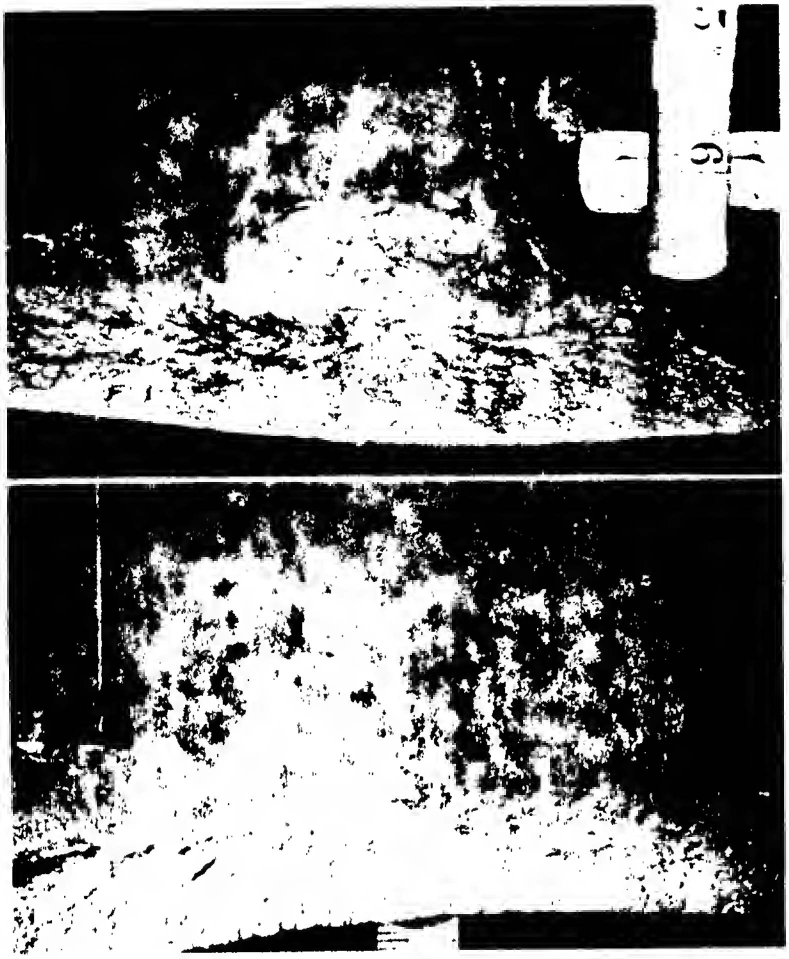


Fig. 17 The starting point of the fracture shown in Figs. 15 and 16

The fracture source (arrows) is at two small arc craters between the fillet weld to the chock base on the after section (*above*) and the toe of the light weld to the clip on the forward section (*below*). × 0.75 approximately.

Fig. 19 Top view of half round (right) and sheer strake (left) shown in Fig. 18

***C* and *D* show locations of specimens cut from sheer strake and half-round for metallographic examination and hardness tests. *E* and *F* indicate vertical longitudinal cracks in the top of the half-round under the weld, *W*, to the chock base. *S* indicates a third vertical crack, which became the source of the main fracture. Note the extent of corrosion in the top parts of the cracks, which indicates that they had existed for some time. × 1.**

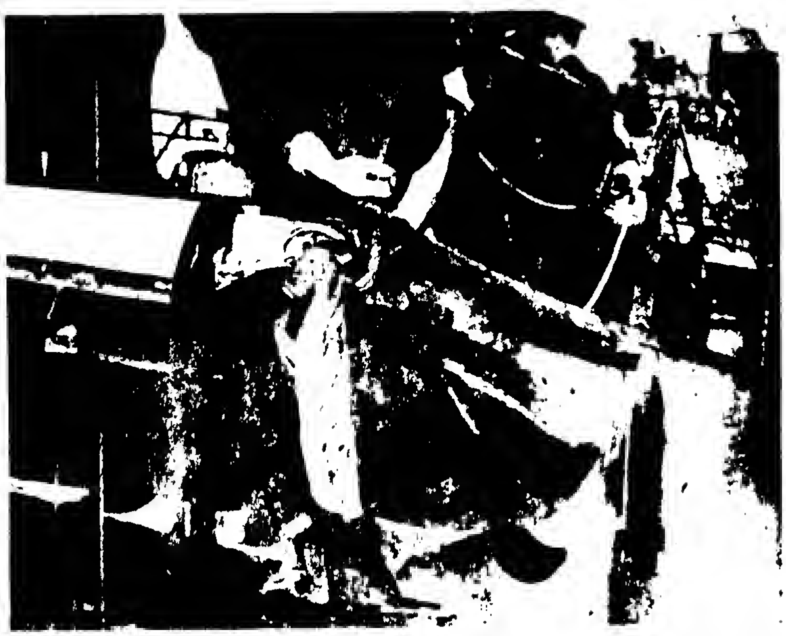


Fig. 18 After section of T1 tanker (NBS Ship No. 61) that broke in two at sea

Pencil indicates origin of fracture, at top of half-round [illegible] bar welded to top of sheer strake. Longitudinal tears and rifts in sheer strake and deck longitudinal resulted from battering of two parts of ship after initial fracture. (Bottom, in relatively warm water, held together for 45 min. after deck and sides had fractured.) (U. S. Coast Guard Photo.)

sensitive than the average for ship plates. At the location of the fracture source, the notch sensitivity was further increased as a result of the small shallow welds and of the previous deformation, or strain aging subsequent to the deformation. The high phosphorus and nitrogen content of this steel suggests that it might be a Bessemer steel, a material which is usually found to be notch sensitive and which is subject to excessive strain aging.[14] This material is not acceptable for use as a strength member in hull structures.[7, 8, *]

An example of a shear fracture in 0.62-in. plate from the side shell of a tanker is shown in Fig. 20. The fracture, propagating from below, was brittle near the bottom of the sample (not shown in the photograph), and changed to the shear type about 13 in. below the longitudinal,

* Both the present[8] and the preceding ABS specifications require that the steel used in the construction of the hulls of vessels shall be made by either or both the open-hearth or the electrical furnace process. (Ref. 8, section 39, paragraph 8.) The present specification also specifies a limit of 0.04 % maximum for the phosphorus content.

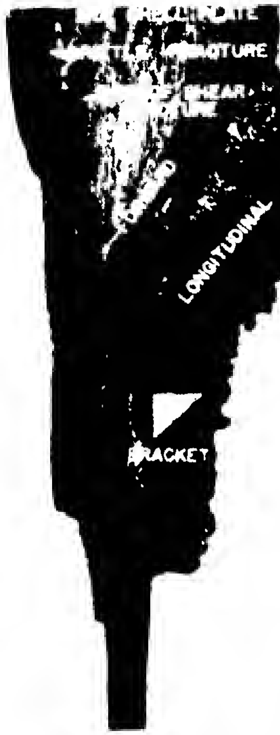


Fig. 20 Example of a shear type fracture in 0.62-in. plate (NBS Plate No. 56B)

The shear fracture, propagating from below, stopped in the plate a few inches above the longitudinal. A brittle fracture, propagating from above and forward, ended when it ran into the shear fracture, indicating that the shear fracture had occurred first and that the brittle fracture occurred under increased stress as the ship broke in two. × ¹⁄₄ approximately.

near the center of the plate width. The shear fracture ran upward and forward, with several sharp changes in direction, passed the end of a longitudinal (at a bulkhead interruption) and ended in the shell plate about 4 in. above the longitudinal. A second brittle fracture propagating from above and forward, ended when it ran into the shear fracture about 2¹⁄₂ in. above the longitudinal. This indicates that the lower (shear) fracture had occurred first at this point, and that the brittle fracture above occurred later as a result of increased stress as the ship broke in two. Accurate determinations of the reduction of thickness could not be made, as the sample was badly corroded and pitted. However, measurements made after cleaning the fracture edges and the nearby plate surfaces indicated that near the brittle fractures the reduction of thickness was of the order of 1 to 4%, the reduction appearing to increase slightly near the point where the fracture changed from brittle to shear type. In the two small areas of double shear fracture, near the bracket, the thickness reduction was about 30%, or more than 10 times the reduction usually observed at brittle type fractures.

Charpy V-notch specimens taken near the shear fracture, near the lower brittle fracture, and at some distance from the fractures showed that the notch sensitivity of the steel was not affected appreciably in areas as near as 1 ¹⁄₂ in. to the brittle fracture. However, the notch sensitivity was increased considerably in the areas near the shear fracture, the effect being noticeable in specimens as far as 8 in. from the fracture. The 15 ft-lb transition temperature of the plate (omitting specimens near the shear fracture) was 2° F, the lowest found for any fractured ship plate tested to date. For similar standard specimens taken with their centers 2 to 5 in. from the shear fracture the average transition temperature was 56° F, the increase probably being due to the deformation and subsequent strain aging.

Charpy V-Notch Test Data

To establish the Charpy V-notch test curve for each plate, specimens were tested at various temperatures in the transition range. Usually 4 specimens were tested at each temperature, and the average value was plotted.

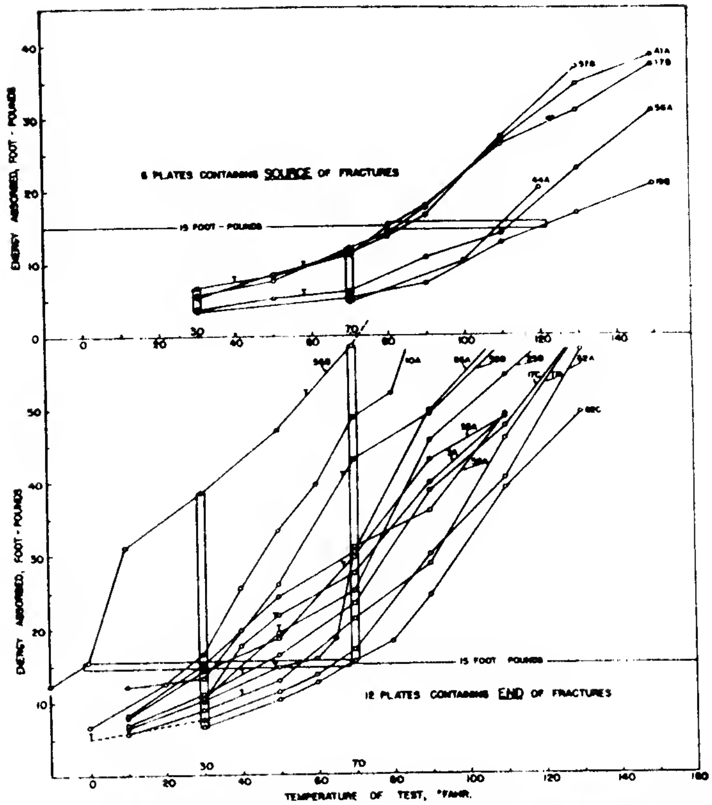


Fig. 27 Charpy V-notch test curves for some fractured ship plates 0.44–0.69 in. in thickness

Horizontal bars indicate range of 15 ft-lb transition temperatures for plates in which ship fractures originated (*above*) and plates in which fractures ended (*below*). Vertical bars indicate ranges of energy absorbed in tests at 30 and 70° F. Temperatures at the time of the ship failures are indicated by the letter *T* on the curves.

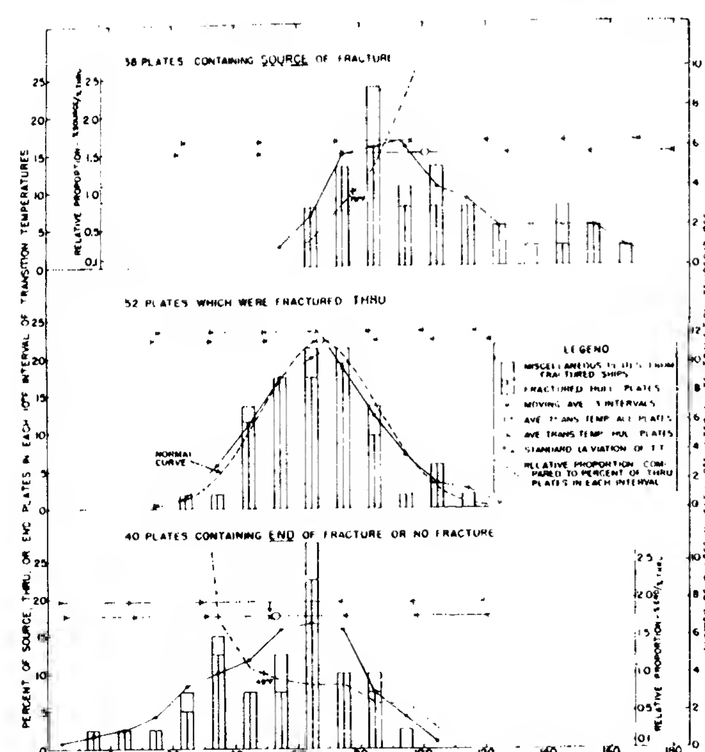


Fig. 30 Frequency distributions of 15 ft-lb transition temperatures of plates in the fracture-source, fracture-through and fracture-end categories

The distribution of the fracture-through plates (*center*) approximates the normal curve. The fracture source plates (*top*) have a higher average transition temperature, and the relative proportion of fracture-source to fracture-through plates in each interval (dash-dot line) increases with increasing transition temperature.

The upper part of Fig. 27 shows the Charpy V-notch test curves for some plates in which fractures in the ships originated, and the lower part shows curves for plates of corresponding thickness, in which fractures ended. The points representing the average values of energy absorbed in the multiple tests of each plate at each selected temperature are connected by straight lines, with no attempt to smooth the curves. The letter *T* on some of the curves indicates the temperature, if known, at the time of the ship failure. To compare the plates at the same energy levels, the temperature at which the curve crosses the line of 15 ft-lb energy absorption is taken as the 15 ft-lb transition temperature of the plate. The horizontal bars superimposed on each set of curves represent the range of 15 ft-lb transition temperatures of the plates in each category, and the vertical bars represent the range of average values of energy absorbed in tests at 30 and at 70° F.

It may be seen that the transition temperatures of the fracture source plates were higher, and the values of energy absorption at corresponding temperatures were lower than for the plates in the fracture-end category. In orther words, the plates in which fractures originated were considerably more notch sensitive than the plates in which the fractures ended.

Part II—Analysis of Factors Contributing to Structural Failures

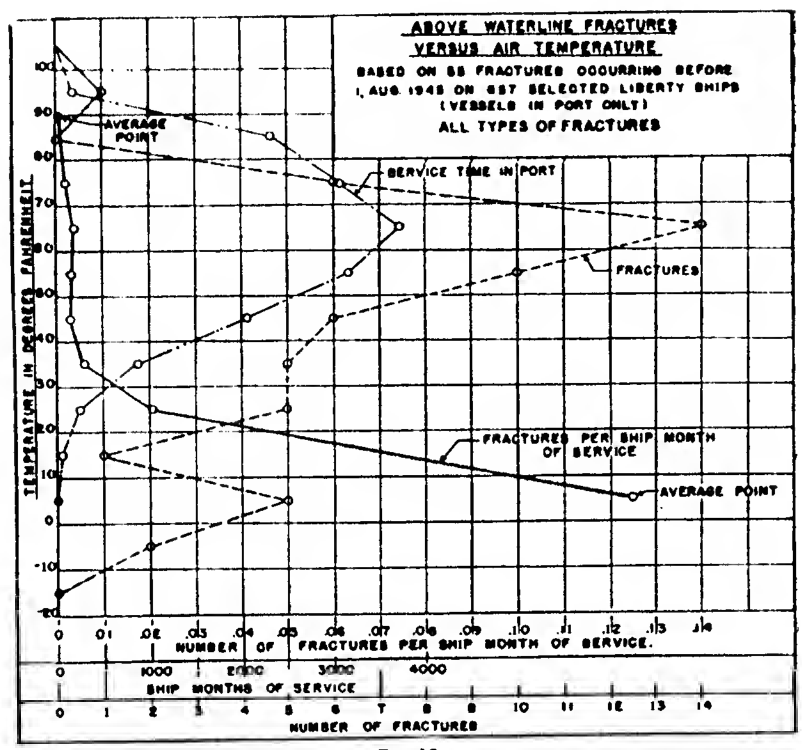


Fig. 13

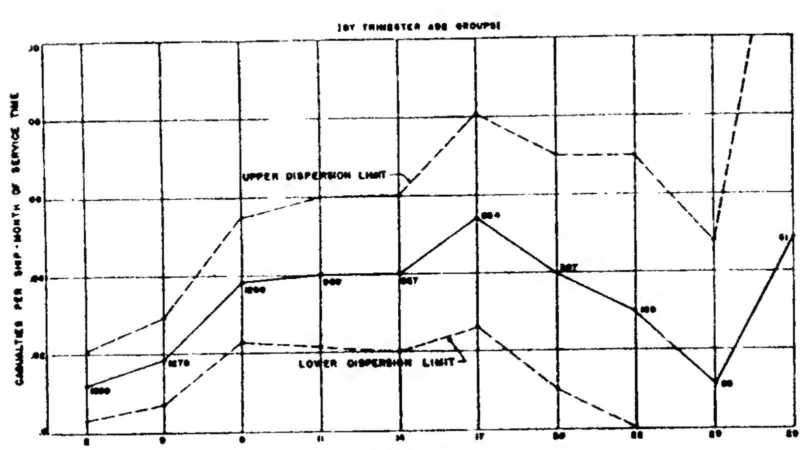


Fig. 14—Casualties per 3-Mo. Period (Winter 1943-44) Divided by Ship-Months' Service in Same Period; Merchant Vessels Built by Maritime Commission (See Table 1)

A Sea and Weather Conditions

In determining the effects of sea and weather, it was necessary to use extra care to avoid misleading results. Ships of different designs might tend toward exclusive use of specific trade routes. For this reason and because there were so many identical subjects, the Liberty ship was used as the specimen for analysis. Existing orders to modify the hatch corners of vessels headed for regions of severe weather conditions tended to segregate the Liberties on a sea and weather condition scale. For this reason, vessels were eliminated from the study when the hatch corners were modified. For the same reason, the newer vessels with design and workmanship improvements were preferred for the more severe services, and this factor had to be considered. The selection finally narrowed down to the 667 EC2 vessels launched before Feb. 1943. These vessels were completed before any structural design details were altered.

From the assembled data based on the 667 Liberty ships launched before 1 Feb. 1943, an attempt was made to ascertain the risk of casualty under varying conditions of air temperature and state of the sea. Various plots were made but it was found that the data were not sufficient to establish casualty risks under known combinations of air temperature and state of sea in such a manner that they would withstand a rigorous statistical appraisal. It was possible, however, to eliminate entirely the effect of sea in a study which was made on ships in port only. The results of this study are presented in Fig. 13 and show the distribution of service time and fractures for various air temperature ranges. This plot includes Class 1, 2 and 3 fractures for the above water line portion of the hull as well as an indication of the risk of casualty in terms of casualty per ship months of service time; all curves are plotted against air temperature ranges.

Although the number of fractures did not permit a complete subdivision on the basis of both sea and weather, it was possible to get a rough idea of what the combined effect of these two items would be. From the approximations made, it would appear that the risk of casualty at the lower operating temperatures and rough seas is many times the risk of fracture in very warm weather and in port.

B. Age of Vessel

The date and age data permit study in many different ways. A sample plotting of winter casualties, Fig. 14, shows that casualty rate is not appreciably affected by age.

C. Loading of Vessel

It was early suspected that poorly distributed cargo loading, under the pressure of wartime necessity, had been responsible for many of the structural failures. It was therefore decided to embark upon a study of the effect of cargo loading and in this regard, information was solicited from

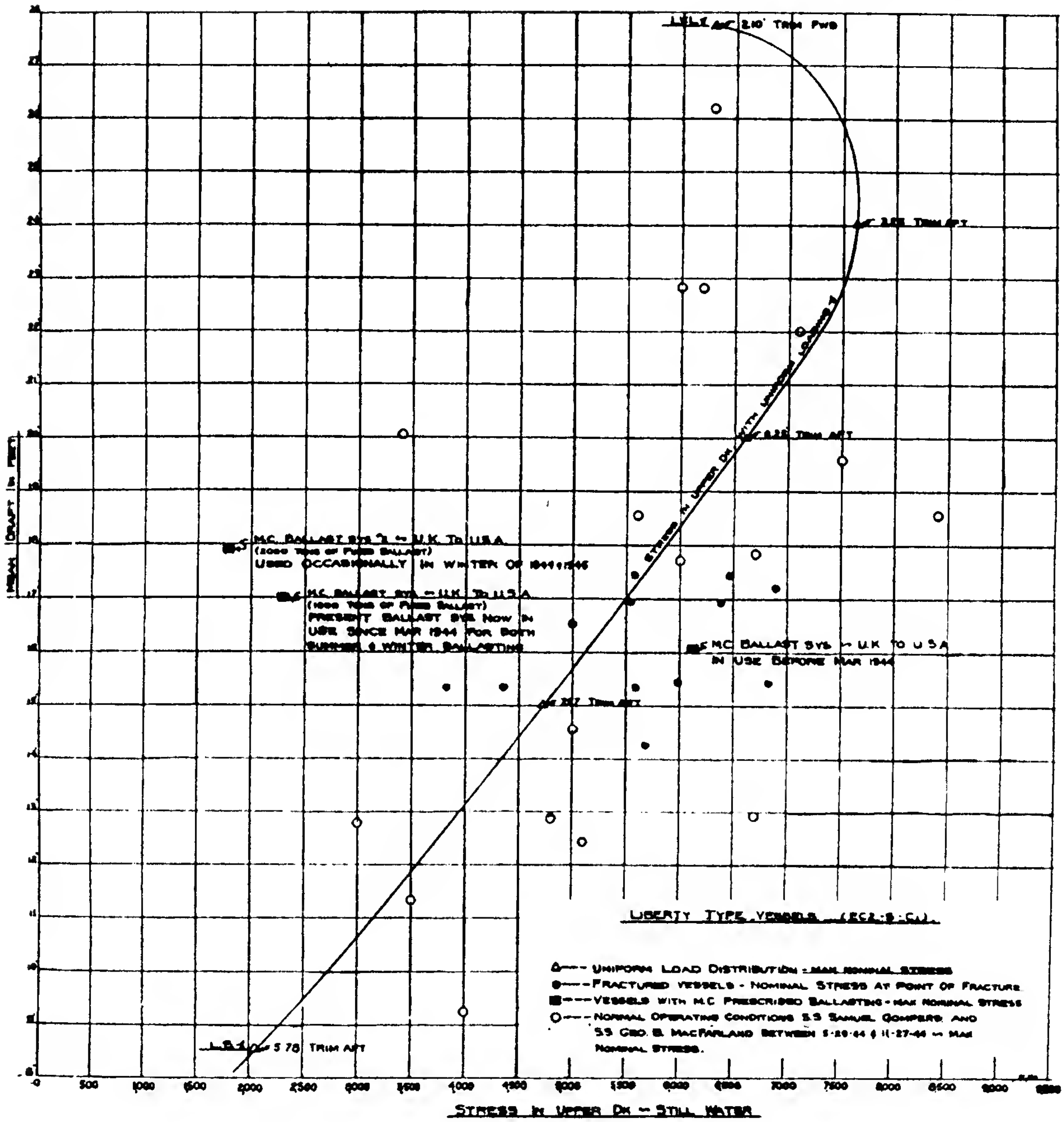


Fig. 16

Merchant Marine inspectors and supplemented by data from the logs of many merchant vessels. The information on the dry cargo Liberty ships presented a great variety of loadings and no rational method for reducing this mass of data was evolved. It was noted from a rough survey that the details of the loading were considerably different, but the fore and aft distribution varied within relatively narrow limits in so far as bending moment on the hull was concerned.

In order to obtain a base line to which comparisons could be made, calculations were made on the Liberty ships at several different drafts with a loading which was uniformly distributed so that the trim was representative of typical operating conditions. Typical trim conditions at various drafts were obtained by recording the fore and aft drafts of 216 ships from the log books. The trim used in the calculation was the average of the scattered plots. From these bending moment calculations, the maximum tensile stress in the crown of the deck amidships was determined and is indicated in Fig. 16 by triangles and a solid line. The maximum nominal stress value in the deck with this type of loading was about 7600 psi tension at 24 ft. mean draft. Comparison between the uniform loading used for this calculation and the numerous loading charts forwarded to Coast Guard Headquarters indicates that the uniform loading was practically typical and can be considered so.

For further comparison, stresses from bending moment calculations performed by the University of California on two Liberties have been plotted as hollow circles. It will be noted that the scatter of points follows the general trend of the line of uniform load distributions. In addition, a calculation was made on a condition representative of the most severe hogging load likely to occur in normal service and the deck stress was found to be 13,750 psi. tension under this abnormal bending load.

Finally, calculations were made on several vessels which had cracked. The nominal stress at the point of fracture is plotted with solid circles. The scatter again centers around the line of uniform loading. This indicates that the loading on the vessels which fractured was apparently not abnormal even though the stress from loading is appreciable.

Although a wide range of cargo distributions can be produced, it can be seen that the actual difference in bending moment between typical normal distributions is not great and little would be gained by attempting to prescribe cargo loading distributions. On the other hand, ballasting presents a possibility for a wider range of variations without interference with good operating conditions. Prescriptions were therefore made up for standard ballasting distributions and are now in use on Liberty ships in the North Atlantic. The nominal deck stresses with the various standard ballasting plans are indicated by boxes on the illustration, Fig. 16. The box indicated as London and Glasgow ballasting represents the ballasting system used before the longitudinal bending moment was a consideration and failures became a problem. The Maritime Commission 1500 ton ballasting schedule is now in use.

A similar but less extensive study was done on the cargo loading on the T2 Tankers. It was found that a much wider possible range existed for the cargo loading conditions with nominal deck stresses reaching 14,540 psi tension under an abnormal load condition. Stresses from uniform loading, however, were even lower than those in the Liberty. They varied in a smooth curve from 6000 psi. tension in the light condition to 600 psi. compression with a uniform full load, the deck stress in lightship condition being the maximum value for a uniformly distributed loading. Loading calculations have been made on two T2 casualties and the nominal stresses at the points of fracture in the sheer strake in one case and in the deck in another was found to be 9900 psi. tension for the S.S. *Schenectady* and 12,150 psi. tension for the *S.S. Esso Manhattan*. It is clear that in the case of tankers, abnormal loading can contribute to the failures but that it can be avoided with greater ease than on the Liberties.

D. Repeated Casualties

Certain vessels have incurred more than one casualty. When a ship suffers two or more failures, there is a tendency to dub her "a lemon." This frequent reaction to repeated failures implies that certain ships by virtue of inherent characteristics are more liable to suffer structural failures. It would be practically impossible to separate the causes of such additional casualties and point to workmanship, fabrication practices, material or to some mysterious unknown factor as the culprit. An attempt was made, however, to get some idea as to whether such "lemons" actually exist.

A probability calculation has been made to determine the number of repeated failures which would result from a random scattering of 922 casualties among a corresponding group of 2580 ships on the assumption that all units are equally likely to attract trouble.

The indication is that after a ship has had a casualty, it is somewhat more liable to a casualty than before the first.

Part III—Susceptibility to Fracture of Different Ship Designs and Structural Details

A. Shipbuilder and Type of Vessel

The various Maritime Commission designs have been divided to show the susceptibility of each design to structural casualties. In addition, the EC2s and T2 Tankers have been listed by shipyard because the number of vessels built by each yard was sufficient to permit a picture of their relative performance. The figures in Table 5 show the number of ships launched in each group, the ship months of service time up to 1 Apr. 1946, the number of casualties of all classes which were reported up to that time and the Class 1 casualties.

A study of the figures shows that no real conclusion can be drawn. Considering only those groups which accumulated more than 3000 ship months of service, it will be seen that the best record with the Liberty ships was in Permanente Yards 1 and 2, and second best was Bethlehem-Fairfield which was the only yard where shell seams were riveted. Considering the Class 1 casualties only, however, it will be noted that the best yard is Bethlehem-Fairfield and second best is New England.

It is difficult to rationalize these results on the basis of workmanship because Bethlehem Fairfield did not exhibit remarkably good appearance in the Welding Advisory Committee's workmanship report and other reliable reports indicate that the quality of hull structure produced by Permanente varied from fair to good as systematic controls were introduced. At the other extreme, Oregon received a poor report from the Welding Advisory Committee and has a correspondingly poor casualty record. Calship is intermediate with a moderately poor casualty record and a good report by the Welding Advisory Committee.

A feeling of confidence in the vessels with riveted shell seams resulted in their assignment to routes where severe weather conditions were anticipated. In light of this and the good performance record under such adverse circumstances, the beneficial influences of riveted seams cannot be denied.

In connection with the Class 1 casualties, the good record of New England is difficult to explain but it should be noted that this yard riveted the bulwark to the top of the sheer strake, thereby eliminating many serious fractures which might have emanated from the bulwark. A similar lack of alignment between serious class and all class casualty results exists in almost the entire table and cannot be explained.

The casualty result on the T2 Tankers is even more difficult to rationalize but it is interesting to note that Marinship, where great care was taken in the structural details and where gamma-ray inspection was used, has a measurably superior record to the other three shipyards. This yard received about the most favorable report of any yard visited by the Welding Advisory Committee.

Sixteen of the 78 Marinship tankers were delivered directly to the Navy. This is a somewhat higher proportion than for the other yards, but the good record of Marinship cannot be greatly affected by this factor because reports of major difficulties on Navy operated vessels did not include any Class 1 casualties for Marinship.

It is gratifying to see the record of the Victory ships as compared to the others. Their record indicates quite clearly that it

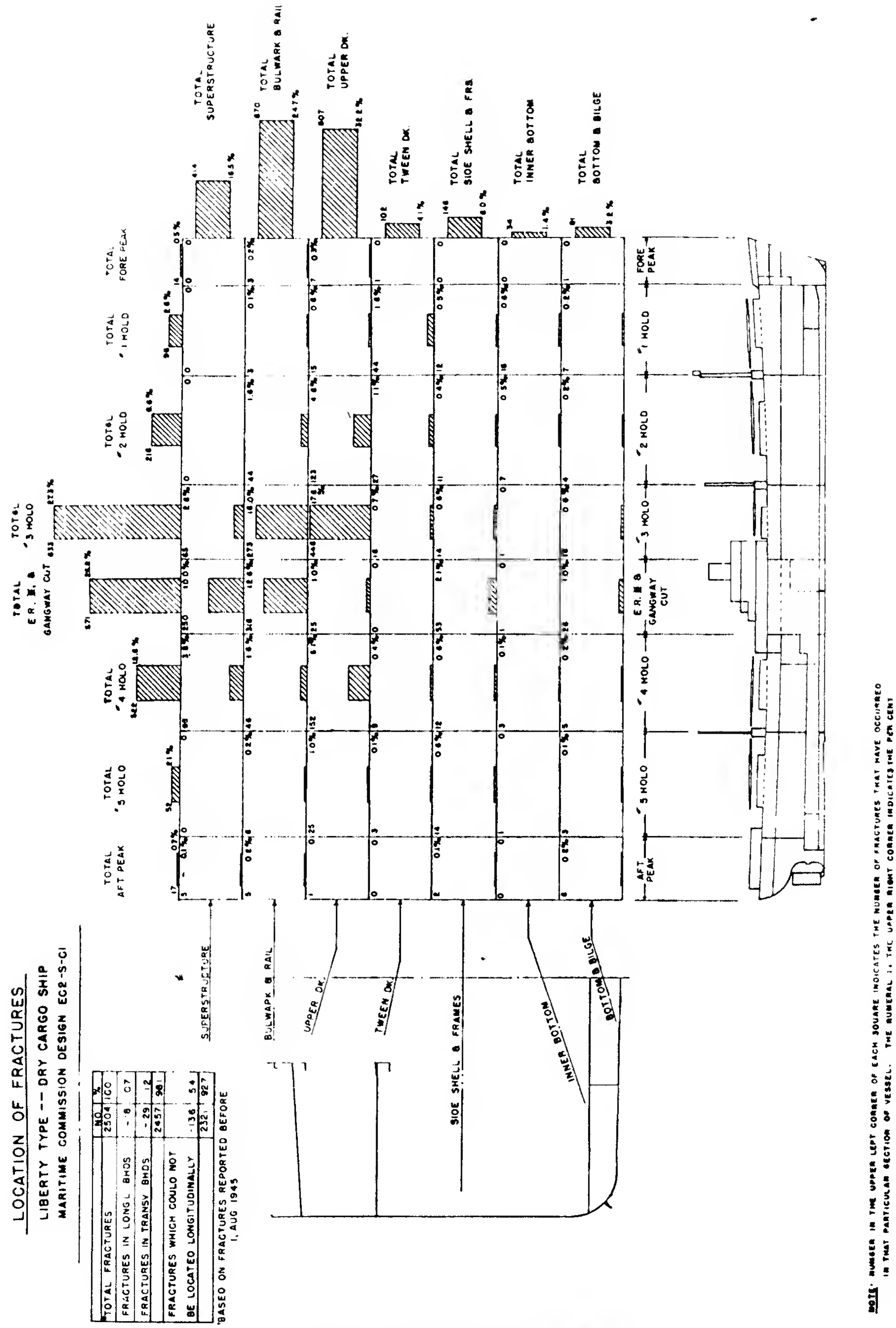

LOCATION OF FRACTURES
LIBERTY TYPE -- DRY CARGO SHIP
MARITIME COMMISSION DESIGN EC2-S-C1
NO. %
TOTAL FRACTURES 2504 100
FRACTURES IN LONGL BHDS -8 0.7
FRACTURES IN TRANSV BHDS -29 1.2
2457 98.1
FRACTURES WHICH COULD NOT BE LOCATED LONGITUDINALLY -136 5.4
2321 92.7
BASED ON FRACTURES REPORTED BEFORE 1, AUG 1945
SUPERSTRUCTURE
BULWARK & RAIL
UPPER DK.
TWEEN DK.
SIDE SHELL & FRAMES
INNER BOTTOM
BOTTOM & BILGE
TOTAL AFT PEAK
TOTAL #5 HOLD
TOTAL #4 HOLD
TOTAL E.R. H. & GANGWAY CUT
TOTAL #3 HOLD
TOTAL #2 HOLD
TOTAL #1 HOLD
TOTAL FORE PEAK
TOTAL SUPERSTRUCTURE
TOTAL BULWARK & RAIL
TOTAL UPPER DK.
TOTAL TWEEN DK.
TOTAL SIDE SHELL & FRS.
TOTAL INNER BOTTOM
TOTAL BOTTOM & BILGE
AFT PEAK
#5 HOLD
#4 HOLD
E.R. H & GANGWAY CUT
#3 HOLD
#2 HOLD
#1 HOLD
FORE PEAK

Fig. 17

Table 5—Shipbuilder and Type of Vessel

Comparison of Casualty Incidence Based on Casualties Reported Before 1 Apr. 1946

Type of vessel and shipbuilder	Number ships launched	Ship months of service	All classes of casualties		Class one casualties	
			Number	Casualties per ship month	Number	Casualties per ship month
EC2-S-C1						
Alabama	20	704	21	0.0298	2	0.0028
Bethlehem-Fairfield	384	10,821	90	0.0083	2	0.0002
Calship	306	10,619	164	0.0154	19	0.0018
Delta	132	3,549	57	0.0161	12	0.0034
Jones Brunswick	85	1,915	27	0.0141	1	0.0005
Jones Panama	66	1,495	14	0.0094	1	0.0007
Kaiser Vancouver	10	369	8	0.0217	1	0.0027
Marinship	15	542	7	0.0129	0	0
New England	236	5,700	72	0.0126	2	0.0004
North Carolina	126	4,085	60	0.0147	5	0.0012
Oregon	322	11,044	215	0.0195	20	0.0018
Permanente	489	15,557	100	0.0064	14	0.0009
Rheem	1	41	0	0	0	0
St. Johns	82	1,908	26	0.0136	1	0.0005
Southeastern	88	2,196	23	0.0105	1	0.0005
Todd-Houston	208	5,542	74	0.0134	18	0.0032
Walsh-Kaiser	10	309	7	0.0227	0	0
Total EC2-S-C1	**2,580**	**76,396**	**964**	**0.0126**	**99**	**0.0013**
T2 TANKERS						
Alabama	102	2,147	22	0.0125	6	0.0027
Kaiser Swan	147	3,283	66	0.0201	6	0.0018
Marinship	78	1,611	4	0.0025	0	0
Sun	203	4,991	101	0.0202	4	0.0008
Total T2 tankers	**530**	**12,032**	**193**	**0.0160**	**16**	**0.0013**
TOTAL VICTORIES	**414**	**5,940**	**33**	**0.0056**	**0**	**0**
All Maritime Comission Ships	**4,687**	**125,985**	**1,441**	**0.0114**	**127**	**0.0010**

Table 6—Casualties Occurring on Various Designs

		Before 1 Aug 1945	1 Aug 45–1 Apr 1946	Before 1 Apr 1946
Emergency	EC2-S-C1	922	43	965
	Z-ET1-S-C3	53	9	62
	Z-EC2-S-C2			
	Z-EC2-S-C5	3	1	4
	EC2-S-AW1			
Tankers	T1	1	0	1
	T2	178	15	193
	T3	18	0	18
Standard Cargo	C1A & C1B	38	3	41
	C2	31	2	33
	C2 Refrig.	40	1	41
	C3	8	3	11
	C4	2	1	3
Combination	P & C			
	C2 P & C	4	0	4
	C3 P & C			
Miscellaneous	C1-M-AV1	4	0	4
	L6	13	0	13
	N3	13	1	14
	V4	0	1	1
Victory	VC2-S-AP2, 3, & 4	14	19	33
Total		**1,342**	**99**	**1,441**

is possible to eliminate most of the fractures by improving design details including riveted gunwales and using more careful workmanship.

Previous reports have mentioned the high casualty rate of the C2 refrigerated ships. These casualties were invariably in the tween decks inside of the insulated holds. The numerous repairs have included rounded corners for the hatches and in several cases, the introduction of riveted seams around the margins of the tween decks. In recent months, the number of failures reported for these ships has dropped markedly indicating that the alterations have been effective. (For other designs see Table 6.)

B. Liberty Ships

A plot, Fig. 17, has been prepared showing the longitudinal and vertical location of all classes of fractures on the Liberty ships. This chart indicates that the fractures peak up near amidships in the upper deck and in the bottom with few fractures in the tween decks, indicating that longitudinal bending stresses play an important part in their distribution. The tabulation also shows the magnifying effect of certain design features such as the hatch corners which were responsible for 612 fractures or 24.4%. The sketch of the EC2-S-C1 vessel indicates the effect quite clearly, Fig. 18.

The distribution of the fractures in the 89 serious casualties occurring up to 1 Aug. 1945, is somewhat different, Fig. 19. In many cases, the damage was so extensive that the starting point was not located. For this reason, it is only possible to identify positively the starting point of 31 casualties involving 42 fractures. Ten of these fractures or 24% started in the sheer strake cut for the gangway ladder. Twenty-two or 52% started in the hatch corner including 48% at No. 3 hatch.

Figure 20 shows the original design of the hatch corner and indicates the three most important sources of fractures. The greatest number of hatch corner fractures occurred in the manner indicated as *A*, second greatest as *B*, and there were several of type *C*. In the case of the type *B* fractures, there was involved a combination of design and workmanship. The abrupt end of the 51-lb. doubler beneath the deck was probably sufficient in itself to start a fracture at so critical a location but in many cases, this was supplemented by a saddle weld in the butt of the deck plating at this point. It was common practice in some shipyards to weld with a Unionmelt machine to within a few inches of the hatch coaming where the automatic equipment had to be stopped. The remainder of the seam was completed by hand welding without further preparation and a saddle weld resulted because of failure of the welding to penetrate the square-edged butt.

Many fractures occur at the sheer strake cut for the gangway ladder and the square ending of the boat deck plate stanchions, Figs. 21 and 22.

It has been noted that the fractures at the center-line stanchion of the second deck almost always occurred as a result of rough weather. The second deck at the edge of the hatch is under high tension whenever there is cargo loaded in the tween decks because the heavy supporting H stanchion is just beneath. Most of these fractures have occurred in the forward end of No. 2 hold and the aft end of No. 1 hold. This is just about where maximum pounding would be expected. The thrust of the bottom force overcoming the inertia of the tween deck cargo produces high stresses in the deck over the H column. In addition, notches around the sole plate of the tween deck stanchion and the ends of brow plates magnify the stress, Fig 23.

Bending tests on the Liberties indicate that the bending stresses in the hull are only slightly reduced by the presence of the deck house. The number of amidship bulwark fractures and shell fractures at the gangway support this. It is curious to note that up to 1 Aug. 1945, the corners of the machinery casings which are similar in design to the other hatch corners suffered

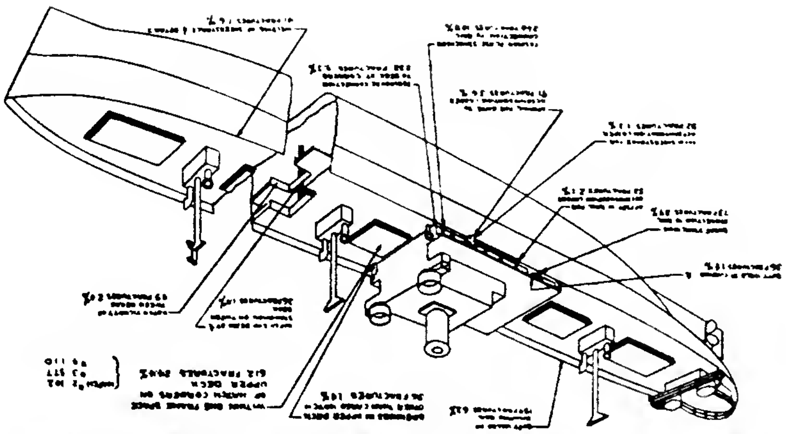


Fig. 18—Liberty Ship EC2-S-C1; Details with Abnormal Frequency of Fractures

These data include 2504 fractures of known origin, occurring before 1 Aug. 1945. One hundred fifty-eight other fractures of indefinite origin were reported.

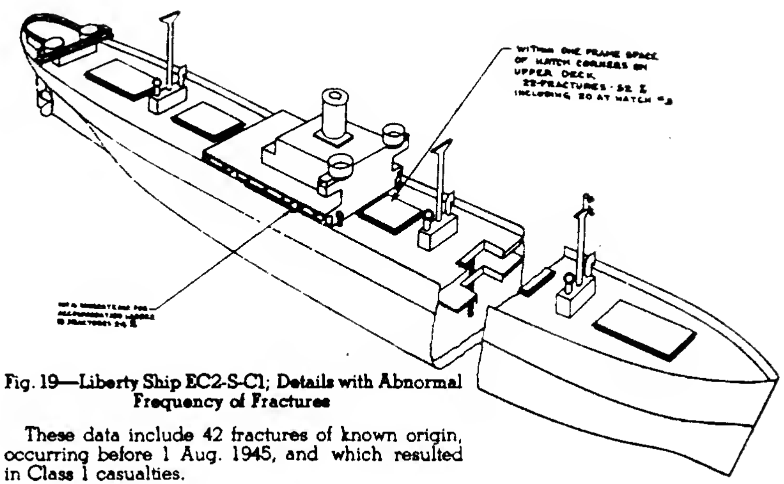


Fig. 19—Liberty Ship EC2-S-C1; Details with Abnormal Frequency of Fractures

These data include 42 fractures of known origin, occurring before 1 Aug. 1945, and which resulted in Class 1 casualties.

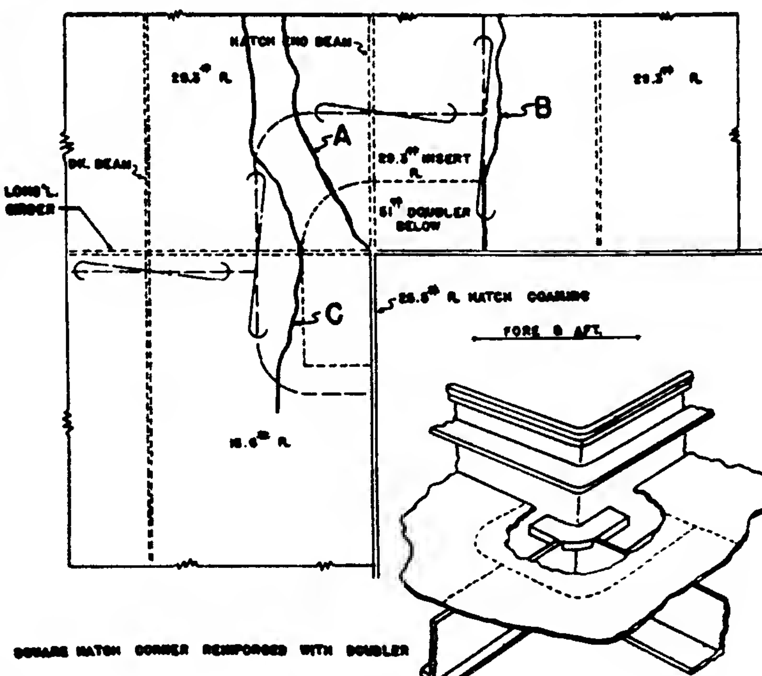


Fig. 20

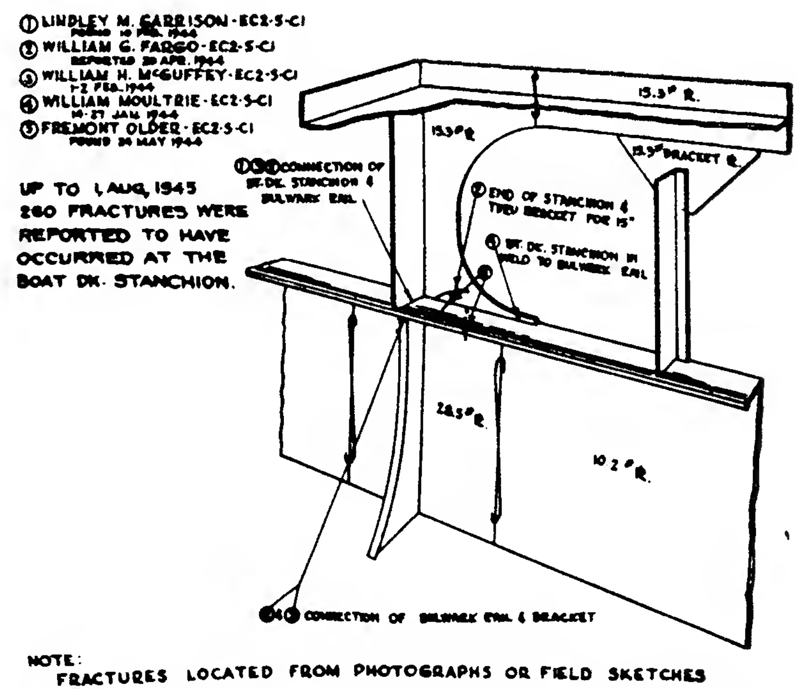


Fig. 21—Liberty Vessel: Composite Sketch of Fractures at Forward Boat Deck Stanchion

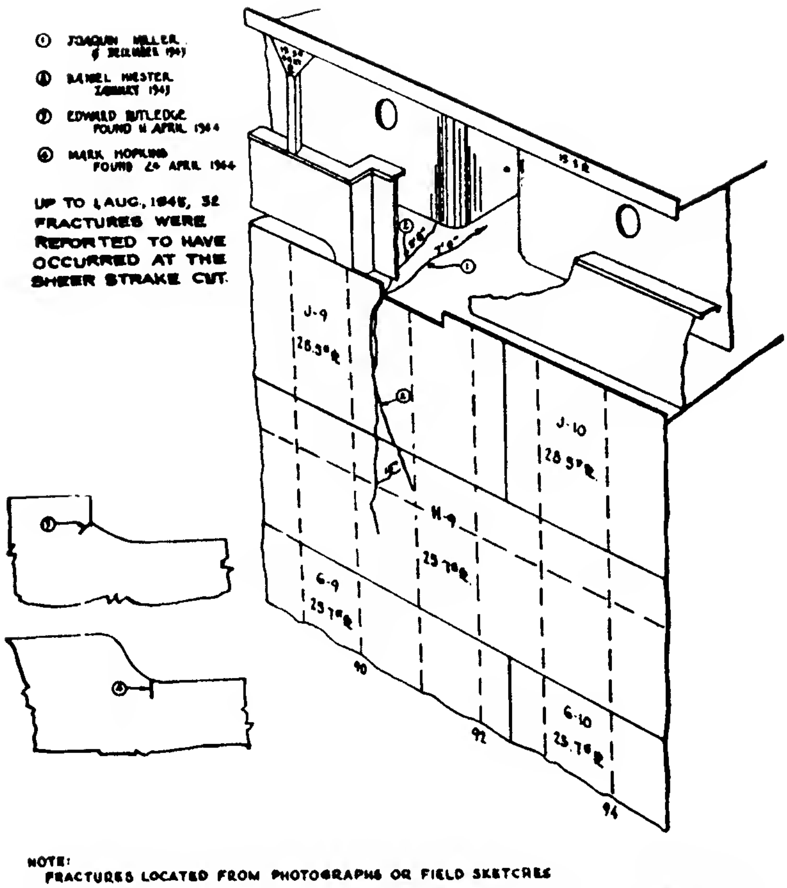


Fig. 22—Liberty Vessel; Composite Sketch of Fractures at Cut in Sheer Strake for Accommodation Ladder

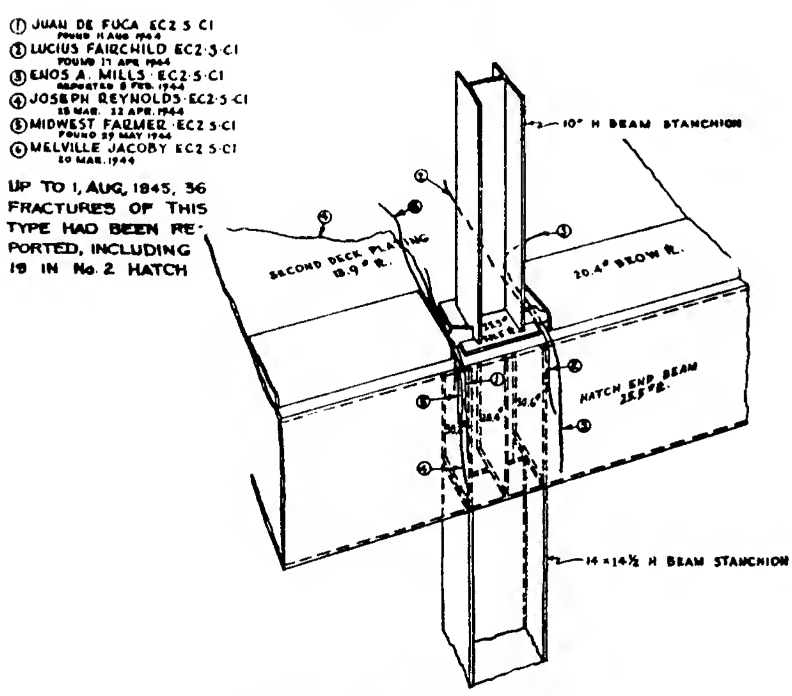


Fig. 23—Liberty Vessel; Centerline Stanchion, Second Deck

less than 13 fractures. Hatch No. 3 suffered 377 fractures and No. 4 110 fractures and the beneficial influence of the warmth in the casing is hard to contest.

It has frequently been held that the hatch corners were not the serious offenders but that many of the fractures emanated at the bulwark or gunwale and ran inboard to the hatch corner. A fracture running from hatch corner to gunwale would warrant grading the casulty Class 1. The Class 1 EC2 casualties include 67 fractures involving the hatch corner vicinity. Thirty-nine of these fractures are known to have originated in the hatch corner. A simple proportion indicates that 5 or 6 of the 28 fractures of indefinite origin probably can be attributed to the details of the gunwale or bulwark. The reported 612 hatch corner fractures do not include these 5 or 6, nor do they include the remaining 22 or 23 which probably originated in the hatch corners.

C. T2 Tankers

The longitudinal distribution of the fractures on the T2 Tankers also shows a peak amidships indicating that bending of the hull is partly responsible for their occurrence, Fig. 24. All of the nine serious casualties occurred in Nos. 3, 4, 5, 6 and 7 tanks.

The source of the failure has been located on two of the ships which broke in two. In the case of the S.S. *Esso Manhattan*, a defective butt weld was the source and in the case of the S.S. *Schenectady*, it was a notch resulting from the combined effect of a design detail and a defective weld. The source of trouble on the two recent T2 Tanker catastrophes is not yet known.

Most of the Class 3 fractures occurred in a detail at the juncture of the transverse and longitudinal bulkheads, Fig. 26. Three hundred twenty five fractures reported before 1 Aug. 1945, at these intersections have been traced to design details which cause a stress concentration under the influence of both hull bending and local hydrostatic loads. It would appear from the longitudinal distribution of these fractures that the hull bending stresses have considerably more to do with the failures than local hydrostatic loading, either static or dynamic.

The sources of these fractures have been located by calculation and test and a satisfactory measure has been devised to ease the offending detail.

One hundred and seventy fractures occurred at the toe of a bracket on the transverse bulkheads, Fig. 27. This is a design detail which can easily be cured and improved arrangements have been fitted in several vessels. A check on the longitudinal distribution of these fractures indicated that they could not be related to the longitudinal bending of the vessel. They apparently result from local loading.

The large number of fractures in the forepeak indicated in Fig. 24 have involved many details of the internal structure. They are local in nature.

D. Victory Ships

Practically all of the casualties on the Victory ships have been Class 3. The fractures reported before 1 Aug. 1945, indi-

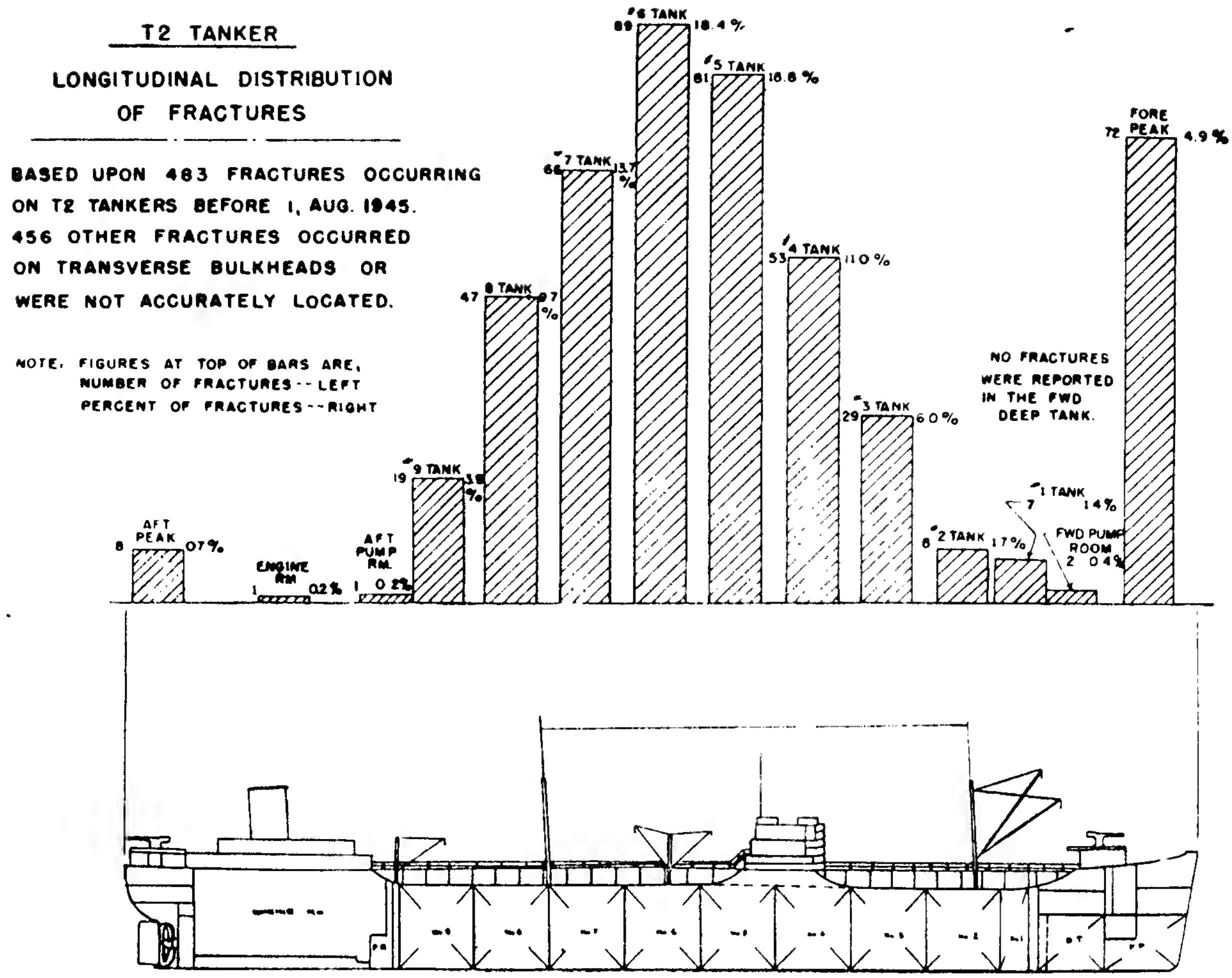


Fig. 24

cate two principal sources of trouble: the bulwark cap rail and plating and the bulwark braces. The casualties occurring before 1 Aug. 1945, included 53 fractures. Eighteen, or 30%, occurred in butts of the bulwark and 27, or 51%, occurred at the toes of the bulwark braces.

Most of the bulwark failures occur at the forward and aft end of the deck house where the bulwark is flanged to land perpendicular to the rounded house front, Fig. 28. This is a poor design detail but is not a dangerous feature because experience with the Liberties led to constructing the Victory bulwarks free of the top of the sheer strake. This freedom prevents the cracks from propagating into the hull.

Most of the bulwark brace failures occurred on the forecastle, Fig. 29. It appears that the load of water resulting from plowing into a wave bends the widely flared bulwarks outward and causes the braces to fail. Sometimes the weld between the brace and deck plating cracks but frequently the deck itself is torn or cracked. This is not serious on the forecastle but it sometimes occurs nearer amidships. Most of the Class 2 Victory ship casualties involve this type of fracture.

Since 1 Aug. 1945, there have been reported five new and curious failures, Fig 30. The masts have broken on five new ships as follows:

Antioch Victory	Foremast	Bethlehem-Fairfield
Mahanoy City Victory	Mizzen Mast	Bethlehem-Fairfield
Brown Victory	Mainmast	Oregon
Waycross Victory	Mainmast	Bethlehem-Fairfield
St. Lawrence Victory	Mainmast	Permanente

The cause of these failures has not been determined but the sources of the steel are being checked.

E. Relative Contribution of Design and Workmanship

The fractures occurring on the EC2-S-CI design have been grouped to determine the proportionate contribution of design and workmanship to the number of fractures which occurred. It is impossible to make a breakdown with a clear line of demarkation between the groups because in many cases, poor design details and poor workmanship went hand in hand in their contribution to the fracture. In other cases awkward design resulted in defective welds because of the difficulty in performing the welding.

Using reported casualty data supplemented by the findings of the research projects for guidance, it has been possible to make a reasonably reliable judgment regarding the part played by workmanship in 1800 of the 2504 fractures reported occurring on the EC2-S-CI vessels before I Aug. 1945. It was found that in 25% of these cases, no fracture would have resulted had good workmanship been used. In 20% of the cases, there was some question but it was believed that the failure might have been avoided had the workmanship been good. In the remaining 55%, the design conditions created such severe notches that perfect workmanship could have done little to prevent the failures.

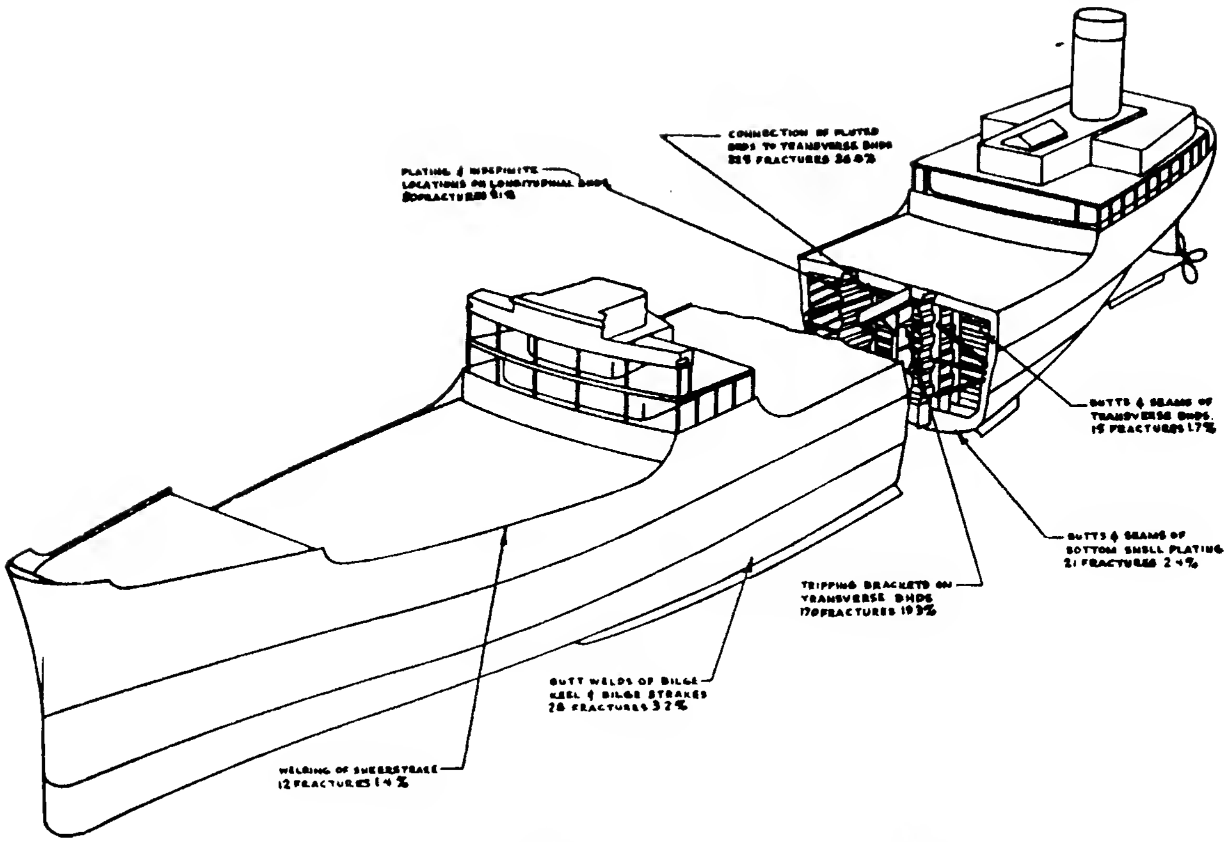
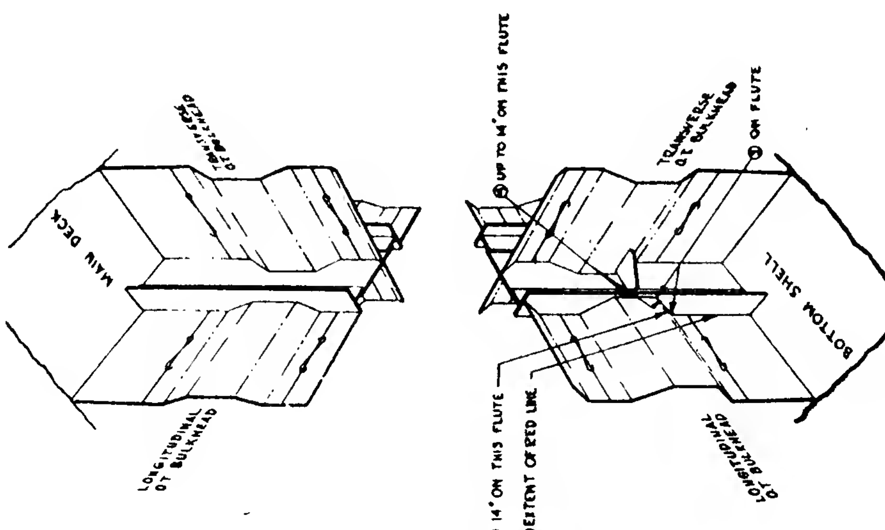


Fig. 25- -T2 Tankers; Details with Abnormal Frequency of Fracutres

These data include 883 fractures of known origin, occurring before 1 Aug. 1945. Fifty-six other fractures of indefinite origin were repored.



① NEW LONDON REPORTED 24 JUNE 1944
② NORTHFIELD FOUND 12 SEPT. 1943
③ CHURUBUSCO REPORTED 12 JUNE 1944
④ RIVER RAISIN REPORTED 7 JULY 1944

UP TO 1 AUG 1945 325 FRACTURES WERE REPORTED AT THESE BULKHEAD INTERSECTIONS.

NOTE: FRACTURES LOCATED FROM PHOTOGRAPHS OR FIELD SKETCHES

Fig. 26—T2-SE-A1 Type; Composite Sketch of Fractures; Connection of Fluted Longitudinal Bulkhead to Transverse Bulkheads

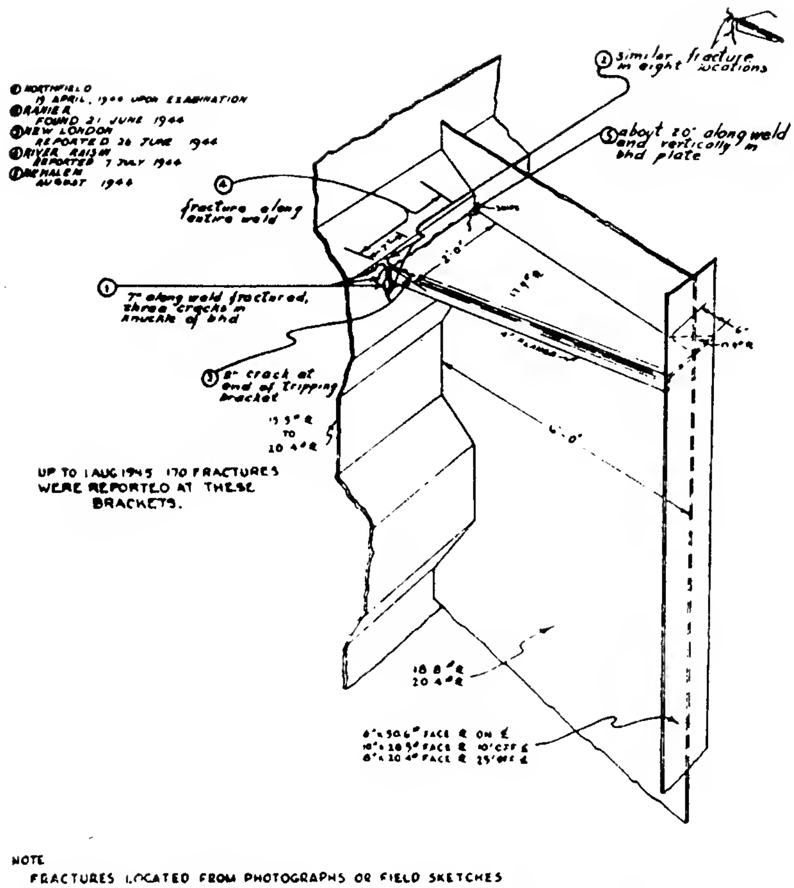


Fig. 27—T2-SE-A1 Type; Composite Sketch of Fractures; Tripping Brackets of Bulkhead Stiffeners on Transverse Bulkheads

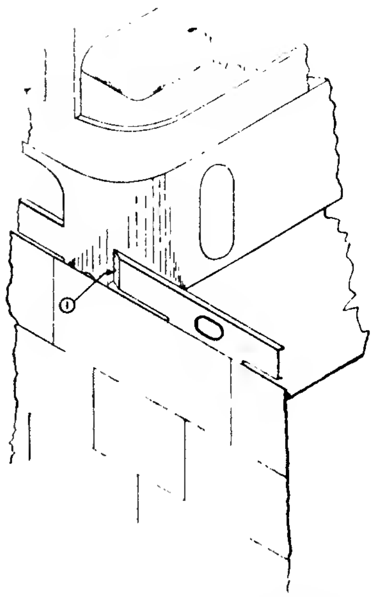


Fig. 28—Victory Ships; Typical Bulwark Fracture at Forward End of Deck House

(1) *Lewiston Victory* 23 Jan. 1946; forward end of P. & S.; aft end P. & S. (2) *Grinnell Victory* before Aug. 1945; forward end, port only; aft end P. & S.

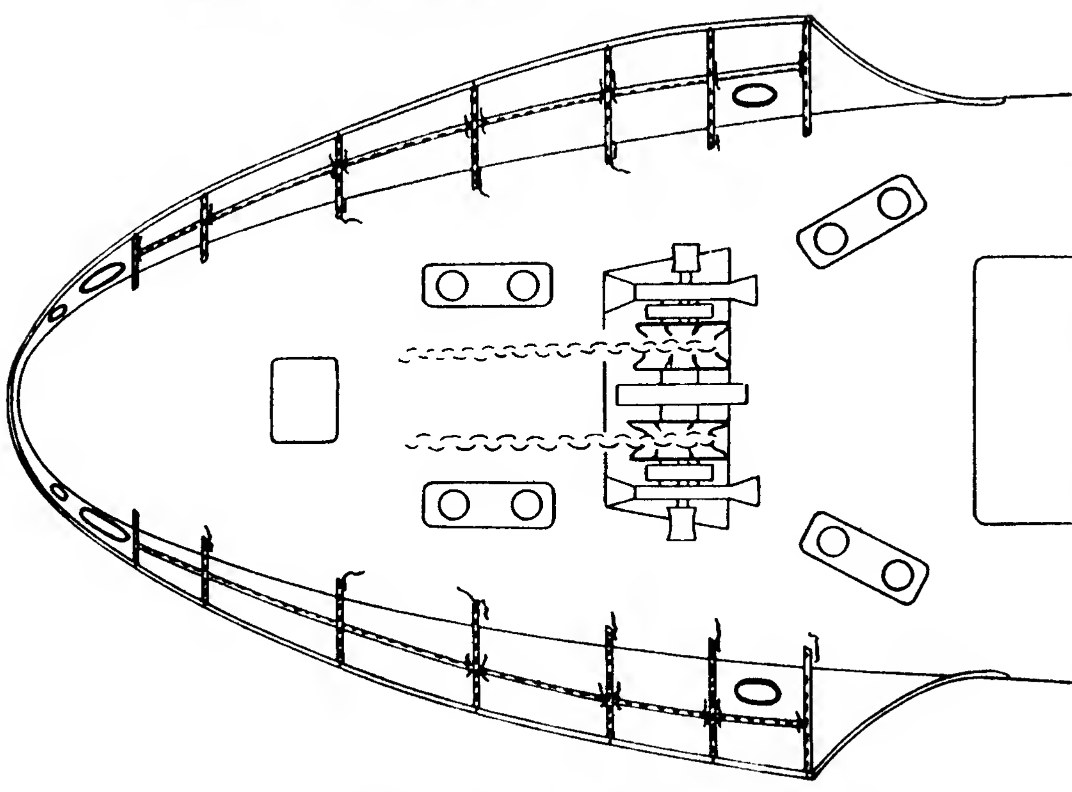


Fig. 29—Victory Ship, Foc'sle Dk., Showing Typical Deck Fractures in *Lewiston Victory* Which Occurred on 23 Jan. 1946

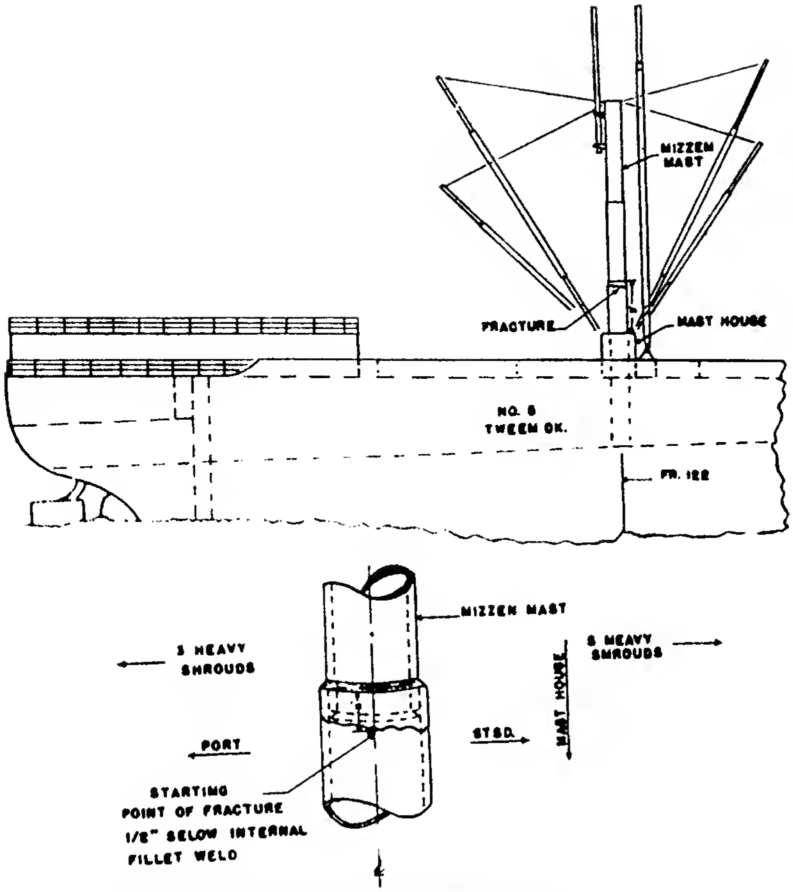


Fig. 30—Victory Ships Showing Fracture of Mizzen Mast of *Mahanoy City Victory* Which Occurred on 24 Jan. 1946

Fracture extended completely around mast except for $8^1/_2$ in. on the fore side.

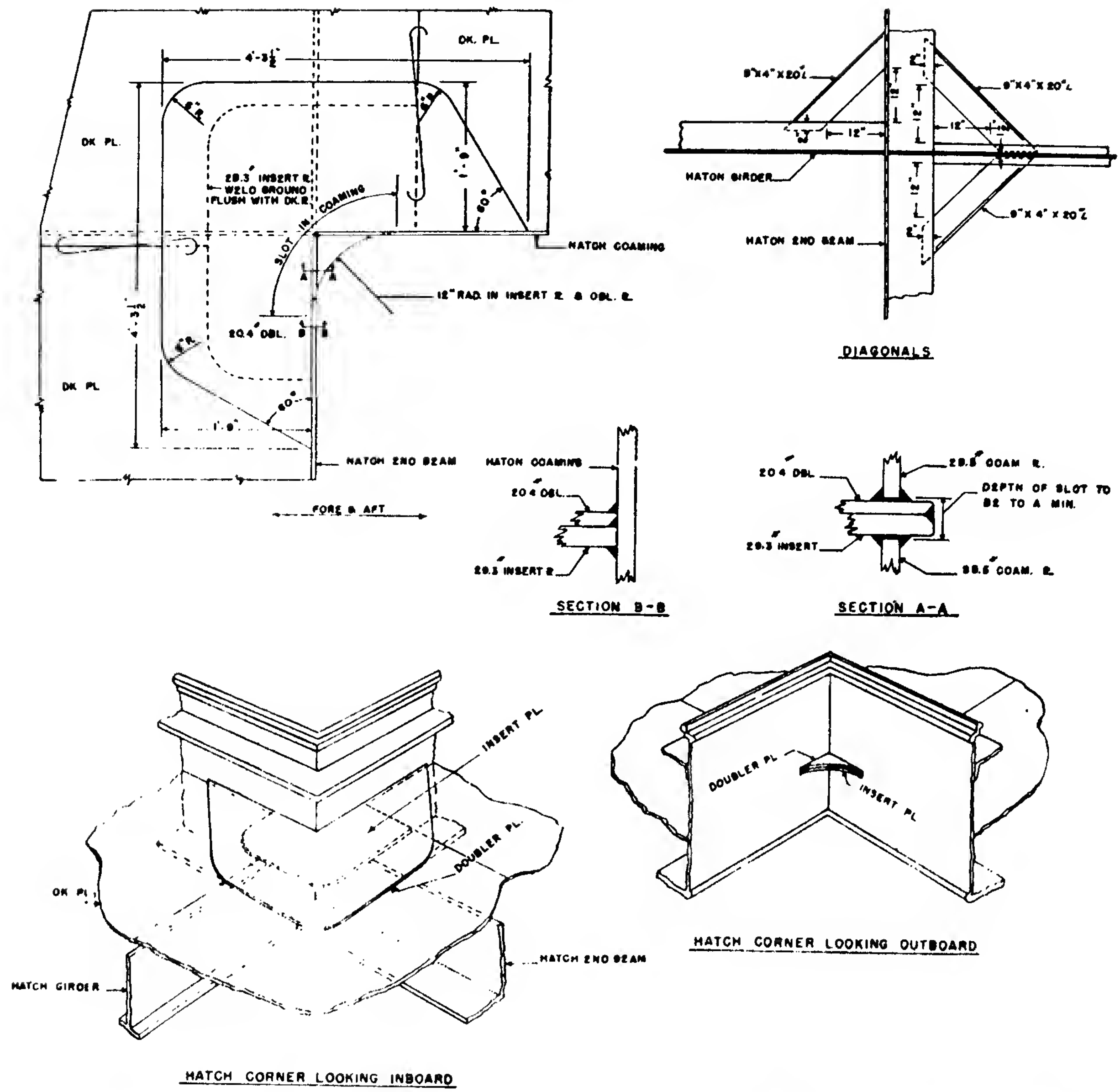
The 25% fractures which could have been avoided by good workmanship include welded butts in the bulb bars in the bulwark and bilge keel. These defective butt welds might have been avoided in the design stage by the use of some other member instead of the bulb bar. The 20% which might have been avoided by good workmanship were practically all at the end of the hatch corner doubler where the participation of perfect workmanship is questionable. It can be seen from this that design contributed to a large proportion of the casualties, far greater than did workmanship.

This should not be taken as an excuse for relaxing the standards of workmanship because many serious failures including the *Esso Manhattan* which broke in two were traced to defective butt welds where poor design played no part whatsoever.

F. Discussion

Almost all of the fractures could be traced to a notch of some sort. This notch might be a design geometry or a defective weld but in practically every case, a real notch could be found. There were a few cases, however, where geometry did not participate. In most of these the fracture commenced at a longitudinal welded seam and spread to port and starboard. In the five Victory ship mast failures, the fractures have occurred near but not in geometrical configurations. In each case, however, they were near welds. The welds in some cases appear to affect the structure apart from creating geometrical discontinuities.

HATCH REINFORCEMENT
CODE NUMBER 1, 2 & 3



CODE NUMBER 1 --- HATCHES 2, 3, & 4 IN UPPER DK
U.S. MARITIME COMMISSION MC PLAN EC2-S-C1-S10-2-3, DETS. 2 & 3
U.S. MARITIME COMMISSION MC PLAN EC2-S-C1-S11-9-9 DETS. 2 & 3
MOORE DRY DOCK PLAN 9997, DETS. 2 & 3
BETHLEHEM STEEL CO S B DIV 56TH ST BKLYN PLAN. T-390 DET 2 & DIAG.
GIBBS & COX, CALSHIP MCE PLAN 1-312-S11-9-4A ALT. XV DETS. 5A & 8A
GIBBS & COX, DELTA MCE PLAN 1-312-S11-6-4 ALT. A DET. 9 (NO DIAG.)
J.A. JONES CONST. CO INC. PANAMA CITY (SK-S11-9-42 DETS 2 & 3)(2-9X-S11-6-49 DET. 2)

CODE NUMBER 2 --- NO DIAGONALS, APPLIES TO TRUNKS 3, 4, 5, 6 & 7 IN UPPER DK
(HATCHES 2, 3, & 4)
U.S. MARITIME COMMISSION MC PLAN Z-ET1-S-C3-S10-2-3 DET. 2

CODE NUMBER 3 --- HATCHES 2, 3 & 4 IN UPPER DK.
PERMANENTE METALS CORP. RICH. 2 PLAN RS10-2-3-1
30.6# DOUBLER & DIAGONALS, NO INSERT PL.
OREGON S B CORP. SIMILAR BUT EARLY HULLS HAD 20.4# DBL.

Fig. 31

ENGINEERING CASE LIBRARY

ECL 1007C

BRITTLE FRACTURE AND STRUCTURAL FAILURE OF THE LIBERTY SHIPS DURING WW-II (C)

NBS Summary

Part IV - Effectiveness of Certain Structural Alterations

Part V - Steel Quality

(Extract from The Welding Journal, July 1947)

The Structural Reinforcement of Liberty Ships
(Extract from The Welding Journal, September 1944)

NBS Summary

Part III - Discussions and Summary

(Extract from The Welding Journal, July 1947)

A Summary of Alterations Performed on Liberty Ships

Table 8 shows the number of vessels of various types which have been altered in accordance with requirements which have been issued. It will be seen that hatch corner reinforcements have been fitted on practically all of the vessels and that riveted crack arrestors have been fitted on a great many. Compliance with current requirements involves immediate addition of hatch corner reinforcements, deck and gunwale crack arrestors on all passenger-carrying Liberties. Cargo ships must have hatch corner reinforcements and gunwale crack arrestors before issuance of the annual inspection certificate beginning 30 June 1946. All alterations will therefore be completed by 30 June 1947.

ARG, ARV, and IX (unclassified).

B. Hatch Corner Reinforcements on Liberty Ships

Figures have been prepared to show the relative effectiveness of the various types of hatch corner reinforcements prescribed for the Liberty ships. The results up to 1 Aug. 1945, are tabulated in Table 7.

The above table should not be considered a true statistical presentation of the relative merits of the hatch corner reinforcement designs because it is impossible to determine the weather and sea

Table 7

Type of hatch corner reinforcement	Ship months of service	Casualties involving hatch corners	Casualties per ship month
Unreinforced	22,146	210	0.0095
Reinforced in service, Codes 5, 6, and 7	17,115	37	0022
Reinforced during construction, Codes 1 and 2	7,722	0	0
Hatch codes 3, 4, and 8, (not approved)	5,403	8	0015
Approved codes 1, 2, 5, 6, 7	24,993	37	0015

service conditions to which the various groups of ships were subjected. The comparison of casualty rates used in Table 7 is a sound method of approach provided the service conditions are identical and the number of cases are sufficient for sampling purposes. Failing this, the traditional method of judging the benefit of alterations by impressions gained in service and as recorded in making up this table must be used. In this connection, we know that the service conditions to which the ships with reinforced hatch corners were subject were more severe than those to which the ships with unreinforced hatch corners were subjected. The comparisons set forth above are therefore conservative. The effective performance of the prescribed hatch corner reinforcements is both gratifying and reassuring. It is reassuring because it demonstrates that reasonable care and practicable designs are capable of easing points in the structure which are known to be sources of trouble.

C. Crack Arrestors on Liberty Ships

The crack arrestors fitted on various designs have proved very effective. They were found to have stopped cracks in 17 instances on 15 vessels which suffered normal structural casualties. In addition there have been reports on four other ships subjected to war and marine casualties where fractures occurred indirectly from grounding or torpedo and mine damage. The crack arrestors stopped eight cracks on these four vessels and the influence of the crack arrestors was questionable in the case of two other cracks. In the case of one other vessel, which ran aground off the coast of California, it is claimed that the crack arrestors were responsible for delaying the complete failure of the vessel and permitting sufficient time to remove the personnel aboard. The details of each case are included in Table 8.

In no case is any crack known to have crossed an arrestor.

Figure 36 was originally prepared to weigh the effects of reducing the length of the gunwale crack arrestor and shows the per cent of the fractures in way of arrestors of various lengths.

Figures 40, 41 and 42 describe a typical case of an effective crack arrestor. The photographs were taken from the location indicated by an arrow on the sketch. The fractured specimen shown was removed from the ship by the British Admiralty and is available for examination at Coast Guard Headquarters.

Many cases have been reported where riveted seams and chain intermittent welding have been responsible for limiting the extent of fracture but such cases have not been tabulated.

D. Gunwale Cuts on Liberty Ships

Thirty-two fractures occurred at the gunwale cut. Of these, 18 were Class 1 and 14 Class 2. Three of the Class 1's had "alterations" No. 5, a rounded gunwale cut. The rest were unaltered.

E. Serrated Bilge Keels

There have been 17 bilge keel fractures. Sixteen of these involved bilge keels which had not been altered. Fifteen of these failures were Class 2 and one was Class 1. Only one altered bilge keel failed. This was a Class 2 failure and the bilge keel was altered with Code 1 (serrated).

Part V—Steel Quality

Defective material might offer an easy explanation of the fractures but such an explanation would be conditional and incomplete.

Samples of steel were removed from several of the ships which fractured, and forwarded to the Metallurgy Division of the National Bureau of Standards, where tests were made to determine their properties. It was usually impossible to test the steel removed from the starting point of the fracture because this usually occurred in a defective weld or a design detail and not in the plating itself. Most of the plates submitted and described in Part V are the first plates through which the fractures progressed as they spread from the starting point.

A. Routine Tests

The material in which the fractures started was tested in the case of many ships, from which samples were taken near the point of origin. Thus 25 specimens from the ships showed agreement with applicable standards of yield strength, ultimate strength and elongation. In addition, the material had passed the usual inspection tests with requirements for sampling and physical properties.

Complete certainty is not assured by these tests, with respect to every part of every piece of steel, but we can be sure that the fractures, which are numerous and widespread in occurrence, do not result from failure of steel to meet specifications.

B. Notched Bar Tests

There are indications that the steel is deficient in a property not covered by the specifications. In the report of the Research Advisory Committee, data are given on this property in relation to notch sensitivity, and the significance of this property for fractures like those seen in the ships has been studied in the laboratory.

Thirty-one steel samples from the ships were given the standard V-notch Charpy test for evaluation of energy absorption in a notched bar. They are designated Group A.

In all cases, the bar was located with notch perpendicular to the surface of the plate, and in such a manner that the notch orientation corresponded to that of the crack as it progressed through the plate. This resulted in placing the bar parallel to the direction of rolling in all cases except on the S.S. *Sea Bass* where the deck plating is transverse. Four bars were tested at each of eight or nine temperatures or about 30 bars per plate.

Data for the 31 plates have been averaged with respect to temperature: the averages are shown in the lower portion of Fig. 44, along with the best and the worst curves. The energy absorption values at 70° F. are also indicated for each of the plates tested (upper left) with dotted lines to indicate the spread of the energy absorption values covered by the four specimens tested at that temperature.

Since the specifications for hull steel do not include notch bar tests, there was no standard value for comparison. For this reason, the Coast Guard Merchant Marine inspectors obtained from the shipyards' stock and scrap piles numerous samples of ½ in. hull steel plate which were forwarded to the United States Naval Shipyard, New York. These are Group B samples. In addition, the Navy had requested the steel mills to submit samples of plate complying with both their own and the American Bureau of Shipping hull steel specifications. These are Group C samples. On Groups B and C a series of Charpy tests was also run, but only at 70° F. The results are indicated on the plots, Fig. 44 (upper center and right). The spread of values was similar to that in Group A and has not been indicated.

C. Chemical Analyses

Chemical analyses were made on the fractured plates from the ships to determine if there was any specific trend which might be indicated on surveying the chemical constituents of the plates involved in the fractures.

D. Temperature and Notch Sensitivity

Figure 44 shows that the steel in fractured plates loses the ability to absorb energy in the notched condition as temperature goes down. Low temperature is said to increase the notch sensitivity of the steel. Experience also shows that fractures in service gain in frequency at lower temperatures. It would be natural to explain this as a result of increased notch sensitivity.

Conclusions

1. The serious epidemic of fractures in the steel structure of welded merchant vessels has been curbed through the combined effect of the corrective measures taken on the structure of the ships both during construction and after completion, improvements in new designs and improved construction practices in the shipyards.
2. Fractures occur more frequently at lower temperatures.
3. By far the greatest frequency of fracture occurs under a combination of heavy seas and low temperatures.
4. Statistically the age of the vessel has no appreciable influence on the tendency to fracture.
5. The longitudinal distribution of cargo on the Liberty ships which fractured was not abnormal and little would be gained by establishing cargo loading prescriptions designed to reduce the number of casualties.
6. The longitudinal distribution of ballast on the Liberty ships including those which fractured was not abnormal but this was improved by changes in the ballasting prescriptions without interfering with operating conditions.
7. In the case of the tankers, poor distribution of cargo or ballast on the tankers can create high stresses more readily than in Liberty ships. General loading prescriptions for tankers appear feasible and desirable.
8. A tendency for certain ships to incur repeated casualties can be measured but the trend is not great.
9. No marked correlation between the incidence of fracture on the ships and the shipyard construction practices could be found. However, with due allowance for difference in design, the ships constructed in yards utilizing subaverage shipyard construction practices showed a higher than average incidence of fracture.
10. Steel removed from plates which had fractured complied with American Bureau of Shipping physical requirements for hull steel.
11. The hatch corner modifications on the Liberty ships have proved effective.
12. The riveted crack arrestor at the gunwale has been effective. Riveted shell seams have also been responsible for limiting the extent of fracture. No crack has been known to pass an arrestor.
13. More fractures started at notches occasioned by design than at notches resulting from defective workmanship. Although the relative contribution of poor workmanship was less, there were important cases where workmanship was the sole cause.
14. Every fracture investigated could be traced to a starting point at a definite geometrical discontinuity involving design or workmanship.

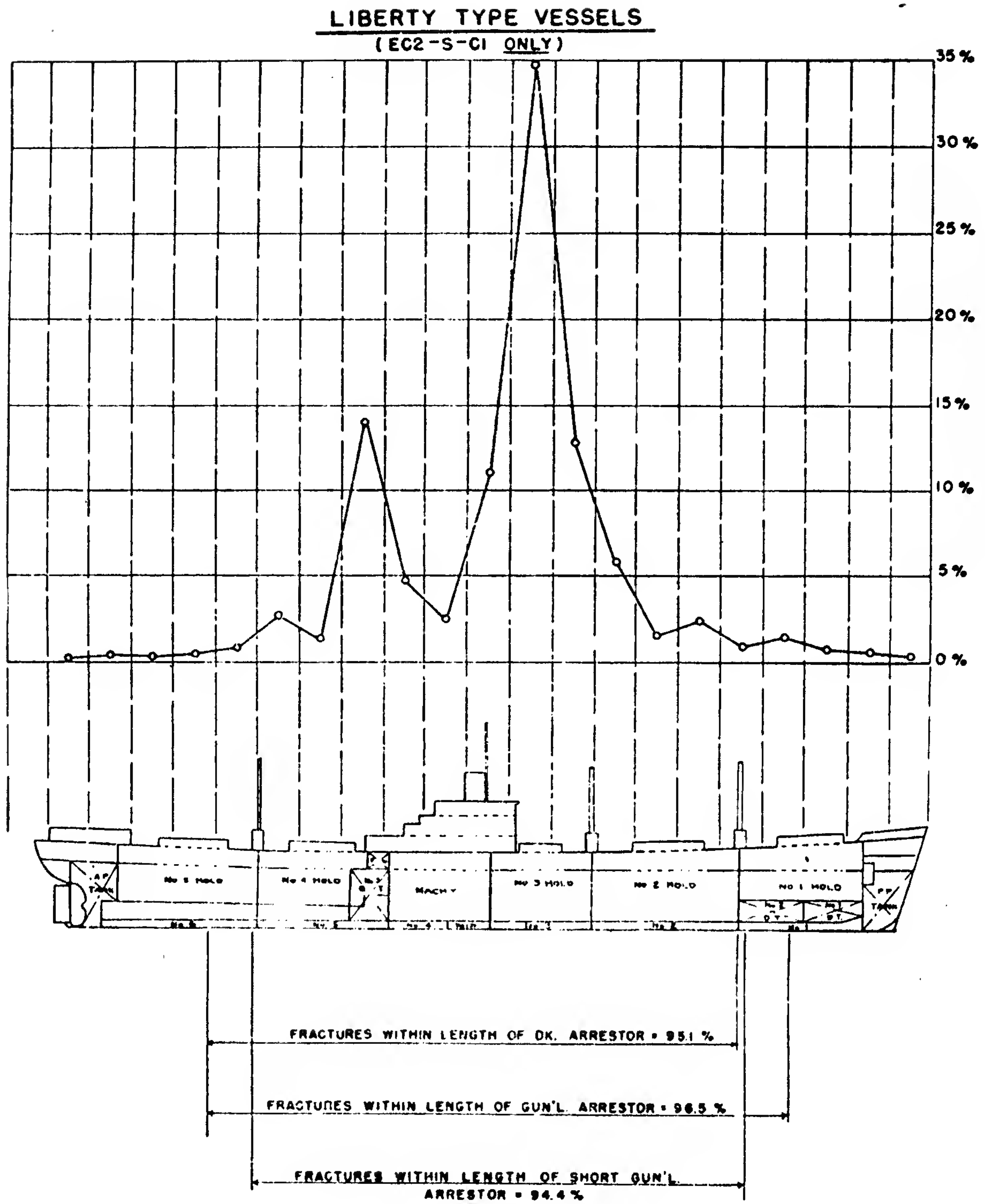
Table 8

SUMMARY OF STRUCTURAL ALTERATIONS ON LIBERTY SHIPS 1, FEBRUARY 1946

U S OPERATED VESSELS ONLY

SHIPS IN OPERATION = 2212
LOST -- WAR = 163
LOST - MARINE = 42
LOANED = 264
TOTAL LAUNCHED = 2711

	Code No.	TYPE OF VESSEL: Troopships & Carriers: AP	KAP	KAPK	XAH	Dry Cargo Ships: XAK-1	XAK-2	XAK-3	XAK-4	XAK-5	AK	XAC	Liquid Cargo Ships: XAO	AO	Misc.: IX	Grand Totals
NUMBER OF SHIPS			17	281	4	1704			1	39	39	24	29	19	22	= 2212
HATCH CORNER REINF'T	1			3		464				30	3	1			23	362
	2												3	8		11
	3					162										169
	4					46										46
	5		16	264		870					10				16	1176
	6												30			68
	7										1					1
	8			10		20			1		3		13	10		56
TOTAL =			16	277		1667			1	30	19	1	30	19	42	= 3047
DK. ALTER.	1			61		283				8	8		7	1	31	428
	2		12	3	1	3				1						20
	3		2		2											3
	4											64				64
TOTAL =			14	24	4	285				7	8	68	7	1	31	= 484
GUNWALE ALTERATION	1			1		278				83		34			18	484
	2			12		40					8		3		7	68
	3		4	2	4	3									1	14
	4		8	4		10							3			38
	5			6		163					6					170
	6					12										13
	7			12		682			1	1	13		28	18	30	787
	8		1	162		126							3			348
	9		1	2		6				1			1			8
TOTAL 5,6 & 7 =			0	60	0	667			1	1	22	0	28	18	20	= 838
TOTAL ARRESTORS =			12	203	4	681			0	66	8	64	10	8	28	= 818
TOTAL =			15	628	4	1418			1	37	28	24	38	18	48	= 1684
I.B. GIRD.	1		14	4	4	11					1		2			= 36
BILGE KEEL	1		1	51		882			1	36	13	24	38	18	33	1208
	2			84		87					4				2	179
	3		11	3	4	72										90
TOTAL =			12	140	4	1151			1	36	17	34	39	18	36	= 1476
REINF'G COMPL.	1		11	128	4	566				36	6	34	10		33	863
	2		2	116		182									3	303
TOTAL =			14	241	4	748				36	6	34	10		33	= 1118



NOTE:
THIS DRAWING IS BASED ON 1736 FRACTURES IN ALL PARTS OF LIBERTY SHIP STRUCTURE AND REPORTED BEFORE 17, OCT. 1944.

Fig. 36

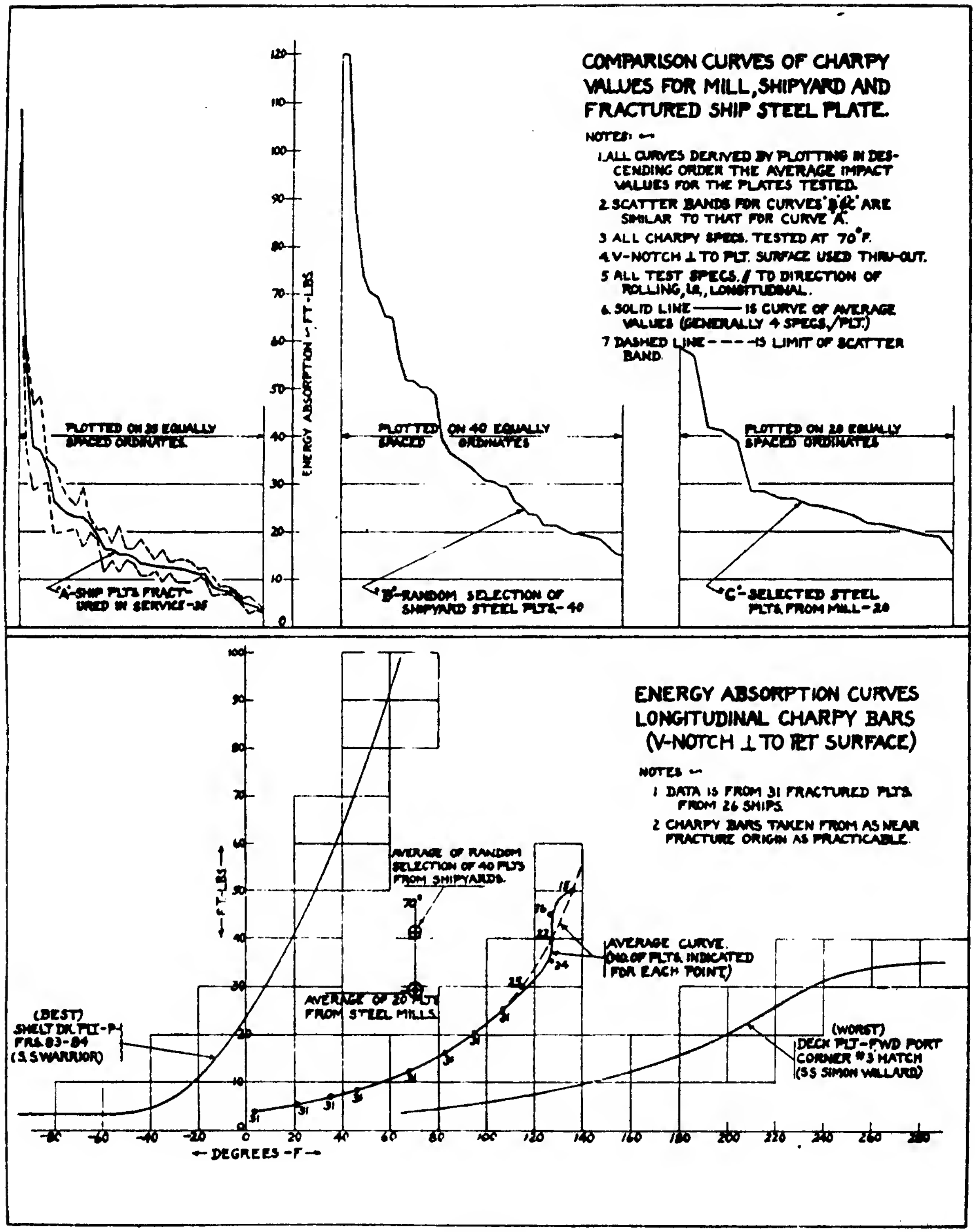

COMPARISON CURVES OF CHARPY VALUES FOR MILL, SHIPYARD AND FRACTURED SHIP STEEL PLATE.
NOTES: —
1. ALL CURVES DERIVED BY PLOTTING IN DESCENDING ORDER THE AVERAGE IMPACT VALUES FOR THE PLATES TESTED.
2. SCATTER BANDS FOR CURVES 'B' & 'C' ARE SIMILAR TO THAT FOR CURVE 'A'.
3. ALL CHARPY SPECS. TESTED AT 70°F.
4. V-NOTCH ⊥ TO PLT. SURFACE USED THRU-OUT.
5. ALL TEST SPECS. // TO DIRECTION OF ROLLING, I.E., LONGITUDINAL.
6. SOLID LINE ——— IS CURVE OF AVERAGE VALUES (GENERALLY 4 SPECS./PLT.)
7. DASHED LINE - - - - IS LIMIT OF SCATTER BAND.
ENERGY ABSORPTION - FT.-LBS.
PLOTTED ON 35 EQUALLY SPACED ORDINATES
PLOTTED ON 40 EQUALLY SPACED ORDINATES
PLOTTED ON 20 EQUALLY SPACED ORDINATES
'A'-SHIP PLTS. FRACTURED IN SERVICE-35
'B'-RANDOM SELECTION OF SHIPYARD STEEL PLTS.-40
'C'-SELECTED STEEL PLTS. FROM MILL-20
ENERGY ABSORPTION CURVES LONGITUDINAL CHARPY BARS (V-NOTCH ⊥ TO PLT SURFACE)
NOTES —
1 DATA IS FROM 31 FRACTURED PLTS. FROM 26 SHIPS.
2 CHARPY BARS TAKEN FROM AS NEAR FRACTURE ORIGIN AS PRACTICABLE.
AVERAGE OF RANDOM SELECTION OF 40 PLTS FROM SHIPYARDS.
70°
AVERAGE OF 20 PLTS FROM STEEL MILLS.
AVERAGE CURVE. (NO. OF PLTS. INDICATED FOR EACH POINT)
(BEST) SHELT DK. PLT-P FRS. 83-84 (S.S WARRIOR)
(WORST) DECK PLT-FWD PORT CORNER #3 HATCH (SS SIMON WILLARD)
FT.-LBS.
DEGREES -F

Fig. 44

The Journal of
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The Structural Reinforcement of Liberty Ships

SINCE the inception of the "Board to Investigate the Design and Methods of Construction of Welded Steel Merchant Vessels" numerous specific steps have been taken to control the difficulties which have occurred. There has been a great deal of conjecture in shipbuilding and shipping circles regarding the measures which have been taken and their intended purpose. It has been impossible in the past to disclose the problems in their true light, but now that the difficulties are more fully understood and the scope and gravity of the situation can be evaluated, it is possible to set down the problems that presented themselves and the steps which were taken through the combined efforts of the U. S. Navy, U. S. Coast Guard, U. S. Maritime Commission and the American Bureau of Shipping.

The first step taken was to educate the shipyard personnel, inspectors and surveyors in the more obvious causes which were contributing to the structural failures. Three pamphlets, whose contents were quite similar, were issued. The Coast Guard and American Bureau of Shipping issued instructions to their inspectors and surveyors, and the Maritime Commission printed a handy pamphlet which was circulated to all shipyard personnel in supervisory capacities and to all inspectors and surveyors. At the same time orders were issued to the shipyards to make specific alterations in two or three items on new vessels which were known to have contributed to the failures. These included the elimination of a cut in the sheer strake of the Liberty ships in way of the gangway, freeing of the bulwark from the top of the sheer strake on the Liberty ships, serrating the bilge keel on both the Liberty ships and T-2 tankers, and adding large girders beneath the deck of the T-2 tankers.

By the end of the summer of 1943, the more obvious difficulties had been largely removed from new ships, but it was apparent that there was a tendency in the repair yards to conclude that, since a plate had cracked, it must of necessity have been rolled of defective material. The ship repair yards were removing large quantities of plating in effecting the repairs. Study showed, however, that the material complied with existing specifications and that new material introduced in the repair was, in all probability, in no way superior to that removed. Instructions were therefore issued in Marine Inspection Memorandum No. 64 covering the repairs of structural failures.

It also became evident that the majority of reports of structural failures were not complete enough to permit study of the more elusive causes. New forms were therefore devised for making the reports so that important information would not be omitted. Large diagrams were drawn for the Liberty ships and T-2 tankers on which the location of the fracture or buckling could be indicated and on which spaces were provided for all of the pertinent data so that inadvertent omission of important facts would be avoided. A third form of letter-size, NAV-CG 2752, was devised for reporting structural failures on vessels other than the Liberty ships and tankers. In order to establish definite procedures for making these reports, Marine Inspection Memorandum No. 57 was issued. All of these data were distributed, not only to the Merchant Marine Inspectors of the Coast Guard, but to the Maritime Commission, Navy Department, American Bureau of Shipping, the British Corporation and the British Admiralty, and at the present time structural failure reports are being received through the regular channels of all these agencies.

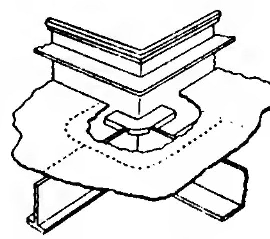

Fig. 1—Outside View of Hatch Corner in Upper Deck of Earlier Liberty Ship Shows Original Design Including 51-Lb. Doubler Beneath Deck and Welding Around Insert Plate

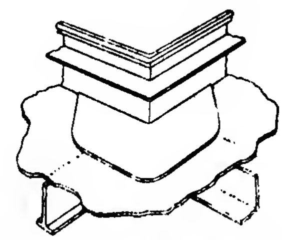

Fig. 2—Outside View of Hatch Corner in Upper Deck of New Liberty Ship. The 20-Lb. Doubler Is Shown on Top of Deck and Covering Insert Plate

The structural reinforcements to be added are intended to serve two purposes: First, steps are taken to eliminate as many crack starters as possible; and second, barriers are introduced to limit the progress of any crack which might start from an undetected origin.

It has been found that practically any square corner introduced into the material may prove a source of difficulty. Square corners are therefore to be rounded in so far as practicable, and, in the case of the hatch corners which are a proved source of difficulty, specific reinforcements are to be added. Figure 1 shows the original reinforcement provided on most of the existing Liberty ships.

On new vessels an improved corner reinforcement is being fitted during the construction period. The reinforcement for new vessels is shown in Figs. 2 and 3. Orders for this change were issued in August 1943. On vessels which were not reinforced at the hatch corner, as shown in Figs. 2 and 3, a rounded insert corner with face plate is being fitted as shown in Fig. 4.

On the earlier Liberty ships a bulb bar bilge keel was used. In welding the butts care was seldom taken to

FACTORS INVOLVED IN THE PREVENTION OF FAILURES

There are three principal factors involved in the prevention of failures of welded structures: First, the material, mostly steel plates and weld metal, should possess, uniformly, the properties anticipated by the designer. Furthermore, these properties must not be affected adversely by the effects of fabricating operations or conditions encountered in service. Second, the design should aim to produce, with economy of materials, weight, and cost, a structure functionally suitable for the purpose intended, with adequate strength in all parts of the structure under all possible operating conditions. Third, workmanship or fabrication—the work of the fitters, welders, supervisors and inspectors—should carry out the ideas of the designer and must produce joints of the strength that he intended. Of course, these three factors are somewhat interrelated, and there may be some other factors involved, such as the cost and availability of materials and fabricating facilities.

The failures in the ships usually involved a combination of these three factors, and were largely a result of the lack of adequate knowledge of (*a*) the significance of certain properties of structural steels, especially their relation to the performance of the steel in the presence of multiaxial stresses or in structures containing notches or other discontinuities, (*b*) the effect of fabricating operations such as welding, flame cutting or cold forming, or of service conditions such as low temperatures, on these significant properties of the steels, (*c*) the distribution of stresses, both uniaxial and multiaxial, in welded ships under different operating conditions and (*d*) the presence of welding defects, and the extent or severity of welding defects that may be tolerated in a structure under the conditions encountered in service.

A number of the fractures originated in parts that are not ordinarily considered as strength members (such as scuffing bars, bulwark plates and cap rails, bilge keels or deck attachments) and propagated through welds into the hull structure. This shows that, even for non-strength members that are attached to the hull by welding, the standards of quality of materials, design and workmanship should be equal to those required in the hull structure itself.

The incidence of failures in welded ships has been reduced materially by improvements of design details and of welding workmanship. However, it is evident that stress concentrations caused by unavoidable structural notches or undetected welding defects can never be entirely eliminated. Even if the original construction approaches perfection, a mechanical or metallurgical notch may be formed at any time during the life of a structure as a result of alterations, accidents, repairs, temporary attachments or even accidental touching of the steel by a welding electrode or an electrical conductor. Many of the failures did originate at such notches, introduced after the ship was in service. This constitutes further evidence that the quality of the steel, especially with regard to notch toughness, must be considered as a most important factor in the prevention of failures in welded structures.

It has been shown that the plates with abnormally high notch sensitivity, in which fractures are most likely to originate, represent the relatively few plates whose notch sensitivity falls in the tail of the probability curve for steels of the quality used when these ships were built. This suggests two possible remedies:

1. Improvement of the average quality of the steel with respect to notch sensitivity, by suitable specification requirements such as composition, grain size or heat treatment. (In effect, this would move the entire probability curve in the direction of decreased notch sensitivity, so that a much smaller proportion of the plates in the tail of the curve would fall beyond acceptable limits of notch sensitivity.)

2. Determination of the notch sensitivity of every heat of steel by inspection tests, and rejection of all heats that fail to meet suitable prescribed standards. (In effect, this would "cut off the tail" of the probability curve.)

The first of these remedies would have the additional advantage that a larger proportion of the steels would have notch sensitivities low enough to halt the propagation of any fracture that might start.

In the application of either of the above remedies, however, due consideration should be given to the possibility that the notch sensitivity of the steel as fabricated in the ship may be considerably greater than the notch sensitivity as determined by mill tests of the prime plate. It has been noted previously that, in addition to the factor of design, nearly all of the fractures originating in plates were associated with welds, flame cuts or deformation of the plate, and in a number of cases notched bar tests have indicated that the notch sensitivity is increased locally as a result of these operations. It is conceivable that this increase might be greater in some steels than in others, so that a steel which appeared to be relatively notch tough in the mill tests might be more notch sensitive, as a result of fabricating operations, than some other steel. For example, McGeady and Stout[22] have shown that the increase of notch sensitivity after welding is much greater for some steels than for others of nearly the same notch sensitivity in the as-rolled condition.

SUMMARY

The results of this investigation indicate that the structural failures in welded ships were caused by stress concentrations and by steel that was notch sensitive at the operating temperatures. This conclusion is confirmed by results of laboratory tests of fractured plates, as well as by critical observations of the starting points and the circumstances of the failures.

The starting points of the fractures could be traced, invariably, to a point of stress concentration at a notch resulting from structural or design details, welding defects, metallurgical imperfections or accidental damage. The failures were relatively more numerous at lower operating temperatures, and the few failures that did occur at temperatures higher than about 50° F were not as extensive or serious as many of the failures which occurred at lower temperatures. The fractures in the ships were of a brittle type, showing very little ductility; but in tension tests the steels from the fractured plates showed normal strength and ductility, which would meet the specification requirements under which these steels were purchased.

All of the above features observed in the ship failures are typical of the behavior of a notched specimen tested in tension or in bending, and are indications that notch sensitivity of the steel was a major factor in the failures. However, the fractures occurred in relatively few of each of the different types of ships that were built, and at different locations in these ships, whereas the majority of the ships of the same design and construction did not fracture. These facts suggest that in relation to the conditions of stress concentration that existed in these ships under various operating conditions, the lack of notch toughness was a borderline deficiency of a relatively small portion of the steels used when these ships were built. That is, although similar notches resulting from design details or welding defects were undoubtedly present in all ships of a given type, fractures originated only when high stress concentrations at critical locations in the structure occurred in combination with plates of usually low notch toughness. This is confirmed by the Charpy V-notch tests of the fractured plates, which showed that plates in which fractures originated in the ships were generally more notch sensitive than plates which did not contain the source of a fracture, using as the criterion of notch sensitivity either the 15 ft-lb transition temperature or the energy absorbed by Charpy V-notch specimens at the failure temperatures of the respective plates.

Statistical interpretation of the data shows that under the conditions existing in a structure such as a ship, the probability that a fracture will originate in a plate increases markedly with increasing

notch sensitivity of the steel. The plates with abnormally high notch sensitivity, in which fractures are most likely to originate, represent the relatively few plates whose notch sensitivity falls in the tail of the frequency distribution curve for steels of the quality used when these ships were built. Similarly, the probability that a fracture will end in a plate increases with increasing notch toughness. Fractures, once started, will continue to propagate in plates of intermediate notch toughness unless the stress concentration falls below that required to promote fracture.[a]

A number of the fractures originated near welds or flame cuts, or at locations where the plate had been deformed in fabrication (such as bilge plates or masts) or during operation. Notched bar tests on some of these plates show that the notch sensitivity in the vicinity of the fracture sources had been further increased by the metallurgical effects of the welding or flame cutting, or by strain aging resulting from deformation. In several cases, fractures originated at arc craters, in plates that were considerably less notch sensitive than the average for fracture-source plates.

The evidence indicates, therefore, that the fractures originated in plates that were "selected" because of higher than average notch sensitivity at critical locations (or notches) in the structure, and that in at least some cases the inherent notch sensitivity of the plates was further increased, in the vicinity of the fracture source, by fabricating operations.

The properties determined by tension tests indicate no relation which is sufficiently marked to differentiate between the plates in which fractures originated and the plates that did not contain fracture sources.

Relations between the Charpy V-notch transition temperatures and the chemical compositions and grain sizes of the ship steels indicate that the notch sensitivity is increased by increasing amounts of carbon or phosphorus, and decreased by increasing amounts of silicon or manganese, or by decreasing the grain size, and that these effects are apparently additive. The improvement of notch toughness that has been attributed to a higher Mn/C ratio is more probably a result of the additive effects of increased manganese and decreased carbon content.

Improvement of the general quality of steels by specification requirements for chemical composition and grain size should be more effective in the prevention of serious failures in ships than a minimum requirement for notch toughness, to be determined by a suitable specification test. The latter would merely eliminate a certain proportion of the potential fracture-source plates, whereas the former would also increase the proportion of potential fracture-end plates.

[a] An even more striking correlation between Charpy V-notch properties and the nature of fracture is shown in the explosion bulge tests conducted at the Naval Research Laboratory,[25] in which many of the unknown or uncontrolled [illegible] eliminated or reproduced under known conditions.

The results of this investigation indicate the importance of notch sensitivity, and the need for more information on the effects of chemical composition, grain size and mill practices on the inherent notch sensitivity of steels. More knowledge is needed also on the changes of notch sensitivity resulting from various fabricating operations, which may be different for different steels.

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INSTRUCTOR'S NOTE

In April 1943, the Secretary of the Navy appointed a "Board to Investigate the Design and Methods of Construction of Welded Steel Merchant Vessels". It is suggested that the class studying this case envision itself as that Board, faced with national responsibility for making urgent and valid decisions. Guided by the instructor the class should see the need to sponsor practical "shotgun" research concerned primarily with design and fabrication, to obtain quick answers even though the solutions are only partial. This was a national emergency and expense was unimportant. However, the class should also recommend a reorientation of the research as soon as the war is over, along more fundamental "basic" lines, emphasizing the materials aspect and seeking a full understanding of the physical and metallurgical facts underlying the behavior of metals and the mechanism of failure.

The primary teaching objectives include an excellent illustration of the engineering approach to a major problem, plus motivation for studies of brittle fracture mechanism, the relationship of welding to structural failures, and an introduction to related metallurgical concepts: the transiton temperature exhibited by body-centered-cubic metals, energy absorption during fracture propagation, design criteria for massive structures.

INSTRUCTOR'S NOTE

I. What should students learn from the case?

A. The engineering approach to a crisis or a national disaster.

1. Immediate search for practical "shot-gun" solutions. The class will be given or should elicit the basic facts known in April 1943, from facsimile sheets distributed by the instructor and by interrogation. A feeling of urgency for action should be imparted by the instructor.

a.) One of the first steps taken by the Board was to recalculate the longitudinal strength of all types of vessels involved in structural failures. These calculations showed a margin of strength in every case over that required by existing standards.

b.) Obviously the class will lack sufficient facts for sound judgment, as did the Board, hence applied research should be sponsored, aimed at design and fabrication changes sufficient to control the brittle fractures. Analysis of the accumulating data will indicate that numerous fractures started at structural discontinuities. Failure at the hatch corners should particularly be noted (in the Liberty Ships 25% of all fractures originated there, and 52% of all serious fractures).

The first remedial step taken by the Board was the modification of cargo hatch corners in 2047 Liberty Ships. A substantial decrease in the incidence of fractures followed.

c.) In an immediate attempt to stop fractures which might otherwise cause possible loss of the vessel, riveted "crack arrestors" were installed in more than 1400 vessels. The arrestors stopped cracks which started in 26 vessels. No crack has been known to pass an arrestor.

2. Search for <u>long range</u> solutions, by research oriented on fundamental lines, seeking "basic" principles.

   The Research Advisory Committee appointed by the Board recommended a study of shipbuilding materials (the effect of welding on structural performance, fundamental factors affecting flow and fracture, practical tests for use in procurement), a study of ship's structure (the ship at sea, design and fabrication of components, testing improved girders to failure), and a study of shrinkage, distortion, and cracking of welded structures during assembly.

B. <u>The relation of welding to the brittle fracture</u> of large structures.

   1. The class will note the different behavior of the same material when tested as a tensile bar or as a large plate.

   2. The requirements for brittle fracture will be clarified: a) low temperature, b) presence of a notch or defect, c) high strain rate (from impact loading or locked up stress).

   3. Brittle fracture is not restricted to ships- this is a general engineering problem.

C. <u>Acquaintance with important metallurgical concepts</u>

   1. Notch sensitivity.
   2. Notched bar test specimens.
   3. Transition temperature in body-centered cubic metals.
   4. Brittle (shear) failure.
   5. Plastic deformation.
   6. Energy absorption during fracture propagation.
   7. Design criteria for massive structures.

Stress concentration factors at the inside radius of the rounded hatch corners were on the order of 2.0. The main superiority of rounded over square corners lies in their capacity for distributing the elastic and plastic action over a greater extent of metal, thereby reducing the local peak values of strain. The inherent danger of notches and sharp fillets in large structures is clearly taught by the fractures of the Liberty Ships.

II. How should the case be used (possible assignments)?

A. First Introduction of the topic

1. Statement by the instructor: "The time is April, 1943". He will impersonate James Forestal, Secretary of the Navy, who has called this class together representing the top engineers of the country, to constitute a "Board to Investigate the Design and Methods of Construction of Welded Steel Merchant Vessels".

2. Summary of extent of disaster as known at that time: There have already occurred over 100 Class 1 and Class 2 "casualties" (fractures which weaken the main hull structure so that the vessel is lost or is in dangerous condition [Class 1], or which involve the main hull at dangerous locations [Class 2]); in fact four ships have actually broken in two.

The instructor here distributes photographs of the four ill-fated ships, and data on five additional vessels due to break apart within the next twelve months.

See "First Assignment, A. First View of the Problem".

The reason for these fractures cannot be explained. The fractures in many cases manifest themselves with explosive suddenness (note descriptions of S. S. Schenectady, Esso Manhattan, Valeri Chkalov) and exhibit a quality of brittleness which has not ordinarily been associated with the behavior of a normally ductile material such as ship steel. Indeed, the first vessel to break completely in two, the S. S. Schenectady, broke apart while tied up at the fitting-out pier. It is evident that these failures of welded ships may have far reaching effects on the country's war effort.

3. Forestal's directive to the Board: ". . . . Make a complete investigation of the matter. . . . and. . . . report the facts. . . . . If the facts establish the existence of defects in the designs of, or in the methods being followed in the construction of such merchant vessels which in the opinion of the Board adversely affect the seaworthiness thereof, the Board will also submit its recommendations as to the measures which should be taken to correct such defects".

4. Relation of welding to the problem.

The advantages of welding in ship construction are numerous. There is a direct saving of weight in the elimination of plate laps, flanged attachments and rivet heads, which may be utilized in carrying additional useful load. In addition, the difficulties associated with riveting in making and keeping structures oil and water tight are obviated. Particularly pertinent to the establishment of new yards in connection with the accelerated program of shipbuilding prior to and during the war was the saving in time, manpower and tool manufacturing capacity effected through the use of welding in lieu of riveting. This saving was brought about by the shorter time needed in welded construction for training operators, and the availability and smaller amount of equipment required, making it possible for a new welding yard to be outfitted and in production in a fraction of the time which would have been required if the yard had been equipped for riveting.

It is safe to say that without welding it would have been impossible to build, in such a short time, the enormous fleet of ships which played such a vital part in winning the war.

There are, however, certain disadvantages connected with welding which were not fully realized at the outset of the expedited building program. Although the technique of depositing weld metal and the application of welding sequences to minimize shrinkage, distortion and cracking were fairly well understood, relatively little

was known of other, deleterious conditions accompanying the welding process on large ship structures. Consequently, when fractures in all welded steel merchant vessels first began to manifest themselves (as in the Schenectady, and Esso Manhattan), conditions were found which did not conform to previous experience. There was a general feeling that the accelerated shipbuilding program and the concomitant quantity production of all-welded ships had resulted in a general disregard for proper construction practices and workmanship. It was particularly felt that insufficient care was being devoted to welding sequences, with the result that locked-in stresses were present in many ships to a higher degree than would be expected. The presence of these high stresses was considered to be an important factor in the incidence of the observed fractures.

However, it must be recognized that structural failures are not confined entirely to welded ships. A few cases of serious fractures in riveted ships are well known, such as the Leviathan and the Majestic, both of which suffered fractures across the strength deck. The chronic occurrence of fractures in riveted ships would have appeared in a different light if the fractures had been generally more spectacular or if the results of research of the war years had been known at the time of their occurrence. When a crack starts in a riveted structure, it generally progresses only to the first break in the continuity of the metal, e.g., a seam. There it awaits reloading to a stress which will give it a fresh start. In a welded structure, however, the crack will continue to propagate as long as sufficient energy is available.

Particularly bewildering phenomena in the welded ship casualties were the appearance and nature of the fracture itself. It was generally believed that medium ship steel incorporated in ship structure would deform elastically when loaded within the elastic limit, and that if it were loaded beyond that point plastic flow would take place and a permanent deformation would result, evidenced by a reduction in thickness or area. If the load were increased sufficiently it was believed that the material would fail only after considerable elongation, as this is the behavior which would ordinarily be expected from a ductile material.

In the observed ship fractures, however, the fractured surface appeared crystalline rather than silky as would be the case in a ductile failure. The break was square and the line of separation normal to the surface of plate, rather than at 45^o as would be the case in a failure on the plane of maximum shear. Very little ductility was evidenced, as indicated by practically zero reduction in the thickness of the plate at the fractured edge. This type of fracture is termed cleavage, denoting a separation of the surfaces of the crystal lattice rather than sliding action along slip planes.

The factors which might cause a normally ductile material to seem brittle were not understood. There was evidently a great need for fundamental study of the mechanism of fracture. As an index of the state of knowledge at the outset of the study, as well as to indicate the experimental difficulties which were encountered, it is considered noteworthy that brittle fractures in medium ship plate of 3/4 in. thickness, comparable to those found in ships, were not reproduced in the laboratory until early in 1944.

5. What first engineering plan of action would the class propose?

   a. The Board immediately took steps to coordinate the efforts of the Navy, Coast Guard, Maritime Commission and American Bureau of Shipping, and embarked upon an extensive program of investigation. Technical and statistical analyses of all casualties were initiated; strength studies were undertaken of each type of vessel involved; loading and ballasting conditions were checked and analyzed; convoy routes with accompanying sea and weather conditions were examined; many specific investigations and extensive laboratory research projects were initiated, aimed at studying design, fabrication and materials used in the construction of welded ships.

   b. The Board requested the National Bureau of Standards to continue an investigation they had already begun, of plates removed from fractured ships.

The Board provided NBS with properly identified samples of plates from 100 fractured ships, obtained through the cooperation of the U. S. Coast Guard. Information was collected on the circumstances of the casualties, structural features of the ships involved, location and extent of fractures, and other details (chemical compositions, probable minimum temperature of plates at time of failure).

c. Class should see need of sponsoring urgent research work of "shot-gun" variety as suggested above, with very practical slant, concerned primarily with design and fabrication.

6. Assignment for next meeting:

Study B. NBS Summary of the 100 Ships

Study C. Board of Inquiry Report

B. Second Class Meeting

1. What has class learned of general origin and source of fractures?

In the Liberty Ships, 25% of all fractures reported originated at hatch corners. Eighteen percent of all fractures were found to occur in the vicinity of No. 3 cargo hatch. In addition, an analysis of serious fractures showed that 24% started in the sheer strake*) cut-out for the accommodation ladder, and 52% started in hatch corners.

Investigations conducted on welded ships revealed that stress concentration factors at the inside radius of the rounded hatch corners of a Liberty Ship at deck level were of the order of 2.0. (A stress concentration of 3.4 was found in a similar corner at sea under dynamic conditions.)

2. What practical recommendations can be made to alleviate the trouble?

*)Defined on page A-2, sketch on page E-1, Fig. 7

a. Improve design and fabrication practices (hatch corner modifications).

One of the first remedial steps which was taken was the modification of cargo hatch corners in the Liberty ships. Ultimately 2047 vessels out of a total of 2212 were fitted with one of several types of hatch corner reinforcements. A substantial decrease in the incidence of fractures followed.

b. Install riveted crack arrestors in existing all-welded vessels.

In an immediate attempt to stop fractures which might otherwise cause possible loss of the vessel a number of "crack arrestors" were installed in various types of vessels. These, in general, consisted of two types, one in which the deck just outboard of the cargo hatch was slotted and a riveted seam strap fitted over the slot, and a second in which either a similar slot and strap were placed in the sheer strake just below the deck line or, in lieu thereof, the deck and sheer strake were connected by a riveted gunwale angle. Altogether, crack arrestors of one or both types were installed in more than 1400 vessels of all types. The gunwale crack arrestors functioned effectively and stopped cracks which had started in 26 cases in vessels on which they were fitted. No crack has been known to pass an arrestor.

3. How does class interpret the sinister statistics about ships named William?

Moral: Beware of misleading comparisons.

The facts: Up to 1 August 1945, 73 ships named William had suffered casualties. This was 5.3% of all known casualties up to that time. In fact, since all 73 Williams were Liberty Ships, which as a class had suffered only 978 casualties, this failure ratio was actually 7.5%. Superstitious sailors naturally took a dim view of this evidence.

The answer: Hopefully, class will eventually ask the instructor how many Liberty Ships had been built in all up to that time? (2710) How many of those were named William? (195) This ratio is 7.2%, making the failure experience quite reasonable.

4. What should be done at end of war, when time becomes available?

   Class should plan to reorient research program along more fundamental or "basic" lines, to study the physical and metallurgical factors underlying the behavior of metals and the mechanism of failure.

5. Assignment for next meeting:

   Study D. NBS Summary (Parts IV and V)
   E. The Structural Reinforcement of Liberty Ships
   F. NBS Summary (Part III)

   Study presentation in modern engineering textbook chosen by instructor of the characteristic behavior of body-centered-cubic metals at low temperatures.

C. Third and Final Class Meeting

1. Discuss the relationship of welding to fracture of large structures.

   Class should understand the inherent danger of notches and sharp fillets in large structures. Class should review concept of notch-sensitivity of steel; mill practices and their effect on the properties of steel; the new specification for shipbuilding steel which was established by the Board

2. Class should appreciate advantages of welding in spite of these dangers:

   Fast construction
   Weight saving
   Water-tight hulls and tanks
   Smoother hull
   Welders are easily trained
   Fabricating equipment is cheap and portable

3. Related metallurgical concepts which should be brought into the discussion:

   Notch Toughness
   Transition Temperature
   Brittle (Shear) Failure
   Plastic Deformation
   Energy Absorption

4. Conclusions reached by investigators at NBS

a) Ship failures can be prevented if:

i. The materials (mostly steel plates and weld metal) uniformly possess the properties anticipated by the designer. These properties must not be affected adversely by fabrication. The quality of the steel, especially its notch toughness, is most important.

ii. The designer produces a structure functionally suitable for the purpose intended, with adequate strength under all possible operating conditions.

iii. The workmanship produces joints of the strength intended.

b) The ship failures were incurred because of lack of knowledge of:

i. The significance of certain properties of steel, especially its performance in the presence of multiaxial stresses, notches, and discontinuities.

ii. The effects of welding, flame cutting, cold forming, low temperatures on the properties of steel.

iii. The distribution of stresses in welded ships.

iv. The presence of welding defects, and the extent of severity of defects which can be tolerated.

c) Two remedies are proposed:

i. Improve the average quality of the steel with respect to notch sensitivity.

ii. Reject all heats that fall below standard.

III. Instructor's Analysis of Student Efforts (questions to stimulate discussion or bring out special features of the case).

A. Was welding the cause of the Liberty Ship failures?

Students should clearly indicate that welding was only an intensifying factor. The failures resulted from the combined effect of stress concentration at notches, in steels that were notch sensitive, exposed to low operating temperature.

B. Isn't it still true that it was only the welded ships that failed seriously or actually broke in two?

No, the NBS report mentions three unwelded failures, including the riveted Oakey L. Alexander (see Welding Journal, Jan. 1948).

C. Isn't brittle failure none the less mainly a problem associated with ships?

The instructor should read Metal Progress, September 1954, pp 83-88. Brittle failure is a general engineering problem. The broad concepts and principles established by the Ship Structure committee apply with equal force to all types of welded structures, be they buildings, bridges, pressure vessels, or ships.

D. In view of the effectiveness of riveted seams and riveted crack arrestors in stopping fractures, why did not the Board logically return to the all-riveted ship?

Answer is summarized in II C 2 above.

E. Were the steel mills guilty of supplying brittle steel to the shipyards?

By today's standards, yes, but the steel as furnished complied with every physical requirement then imposed by specification.

Tests on unwelded flat plates in widths varying from 12 to 72 in. and on large welded structural specimens finally indicated that, in the presence of notches which are comparable to those found on board ship, ordinary ship steel may fail at nominal stresses which were considered extremely low by accepted engineering standards. It should be noted that nominal failure stresses decrease from about 45,000 psi, in the 12 in. plates to stresses approximating the yield point*) in 72 in. plates, and in the welded structural hatch corner tests failures occurred at nominal stresses as low as 23,000 psi.

*) About 36,000 psi.

Studies of the speed with which fractures of the cleavage type propagate have disclosed that it is extremely high (about 5000 ft. per second). This finding substantiates reports which have been received from the masters of vessels which have broken in two in regard to the suddenness with which such casualties have occurred.

F. Were the shipyards guilty of poor welding quality?

The Welding Advisory Committee made a survey of representative shipyards, both Government and private, on the Atlantic, Gulf and Pacific Coasts, and found varying degrees of quality in workmanship and in methods of construction.

Their findings showed the need for improvement in almost every phase of welded shipbuilding, and in particular, the need for standardization in operator training and upgrading. The identification of welding operators by degrees of skill and by individuals was found to be unsatisfactory. In most cases there was no means of tracing defective work to the operator who was responsible. Close inspection, including subsurface inspection of welds, was made in only about one-third of the yards. It was found that the piece work system in use by a great many yards did not serve as an incentive for good work.

Poor workmanship engenders fracture, since a fracture may originate at a small notch, such as is occasioned by peened-over cracks, by undercut welds, by porosity and inclusions in the weld, or by "saddle" welds resulting from incomplete penetration, which leave voids at the center of the joint.

IV. Advances of the Past 25 Years

Obviously there have been great advances in shipbuilding since the publication of the Final Report of the Board of Inquiry. Present day ships are fully welded with no thought of riveted crack arrestors. Super tankers are on the seas; longer vessels are created from short ones by inserting prepared mid-sections; vessels with capacities of 500,000 tons or more are being envisioned.

This new confidence in welded shipbuilding is based principally on today's control of two major factors which influence the soundness of the vessel:

1. The quality of the steel.
2. The engineering design.

The steels used today are usually three grades specified by the American Bureau of Shipping, with controlled ratio of manganese-to-carbon: Grades A, B, and C (for different thicknesses of plate). These steels have a low NIL ductility transition temperature; their notch toughness is in fact so good that impact tests are not routinely required in the specifications, excellent performance being assured if the other requirements are met: for example, fine grain practice is required for Grade C. Beyond this, some use is beginning of alloy steels with special impact properties. Passenger ships have incorporated T-1 steel and other alloy steels in strategic places for greater security.

The design must have no stress raisers. Notches are prohibited, a lesson well taught by the Liberty Ships. The bulwark plates for example are not square-ended into the sheer strake, but now have rounded ends.

What about weld quality? Given good steel and good design, it appears that minor defects in the weld become of lesser importance, Qualification tests for welders and welding filler materials assure a performance level adequate for the intended service.

Additional Documents for Instructor's File

1. Summary of M. E. Shank article,
   Welding Research Council Bulletin 17, Jan. 1954

2. Structural Failure of a Riveted Ship
   Proceedings of Merchant Marine Council, May 1947

3. Brittle Failure of Steel Structures - a Brief History - by M. E. Shank
   Metal Progress, Sept. 1954

4. Hatch Corner Deck and Side Shell of a Shelterdecker

5. 30 Years Ago - Loss of all-welded "Joseph Medill"
   Welding Engineer - Oct. 1966

Summary of M. E. Shank Article (Welding Research Council Bulletin 17 January 1954)

Major concern for brittle fracture as an engineering problem began with the merchant ship failures during and after World War II. Of some 4700 welded ships, 250 suffered severe brittle fractures that endangered the vessels (19 of these actually broke in two or were abandoned) and 1200 suffered potentially dangerous cracks of somewhat lesser severity.[64-65]

Extensive investigations of the merchant ship failures prompted the realization that other major brittle failures had probably occurred without necessarily having been recognized as such. A survey of Shank[66] of earlier brittle failures of engineering structures other than ships, is something of a classic, it describes 20 failures of storage tanks including the famous Boston molasses tank failure of 1919 which released 2 1/2 million gallons of molasses, killed a dozen people by injury or by drowning in molasses, injured 40 others, drowned many horses, damaged many houses, and knocked over a portion of the Boston elevated railway structure. Details of the failures and opinion of experts are documented from the court record, and an interesting commentary is the summary of the court-appointed auditor, who describes the conflicting nature of the testimony and describes the state of knowledge of such failures at that time in the statement "that the only rock to which he could safely cling was the obvious fact that at least one-half the scientists must be wrong." This failure admittedly has limited significance in a consideration of possible nuclear vessel failures, but it illustrates some of the uncertainties that even today surround the subject brittle fracture and it further demonstrates that the incidental results of a failure can be compounded beyond the simple fact of a vessel failure.

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[64] U. S. Navy Department, Final Report of Board of Investigation to inquire into the Design and Methods of Construction of Welded Steel Merchant Vessels, July 15, 1946, U.S. Government Printing Office, 1947.

[65] H. G. Acker, Review of Welded Ship Failures, Report to the Committee on Ship Structural Design, National Research Council-National Academy of Sciences, Report SSC-63, Jan. 12, 1953.

[66] M. E. Shank, A Critical Survey of Brittle Failure in Carbon Plate Steel Structures Other Than Ships, Welding Research Council Bulletin 17, January 1954.

Shank's survey records several structural failures of bridges, crane booms, stacks, and penstocks, but only a few actual failures of pressure vessels; several of these failed during pressure testing rather than in service. One of the vessel service failures was that of a hydrogen storage vessel in 1943. Another was the famous 1944 failure of two storage vessels that released large volumes of liquified natural gas into the Cleveland sewer system and resulted in fires and explosions that caused the death of 128 people and damage estimated at $6,800,000. Shank also reviews the limited available information on a number of failures of gas transmission lines between 1948 and 1951 and makes some speculations that have since proved remarkably accurate. Subsequent tests on pipelines will be discussed later.

One of the most significant, and now obvious, characteristics of the brittle failures discussed by Shank, as well as the many failures in merchant ships, is the fact that practically all occurred in winter when the ambient temperature was low, and frequently when the temperature was changing rapidly.

Puzak, Babecki, and Pellini[67] have summarized the relationship of experimental NDT determinations to the World War II ship fracture failures and to brittle failures in six pressure vessels and about 10 nonpressurized engineering components which they studied in detail. They conclude that the energy criteria of the Charpy V-notch test used to establish NDT and related temperatures provide the best practical method for notch-ductility indexing of steels, and that Charpy V-notch specifications intended to prevent brittle fracture should be based upon demonstrated NDT correlations that have been established by service data or drop-weight tests.

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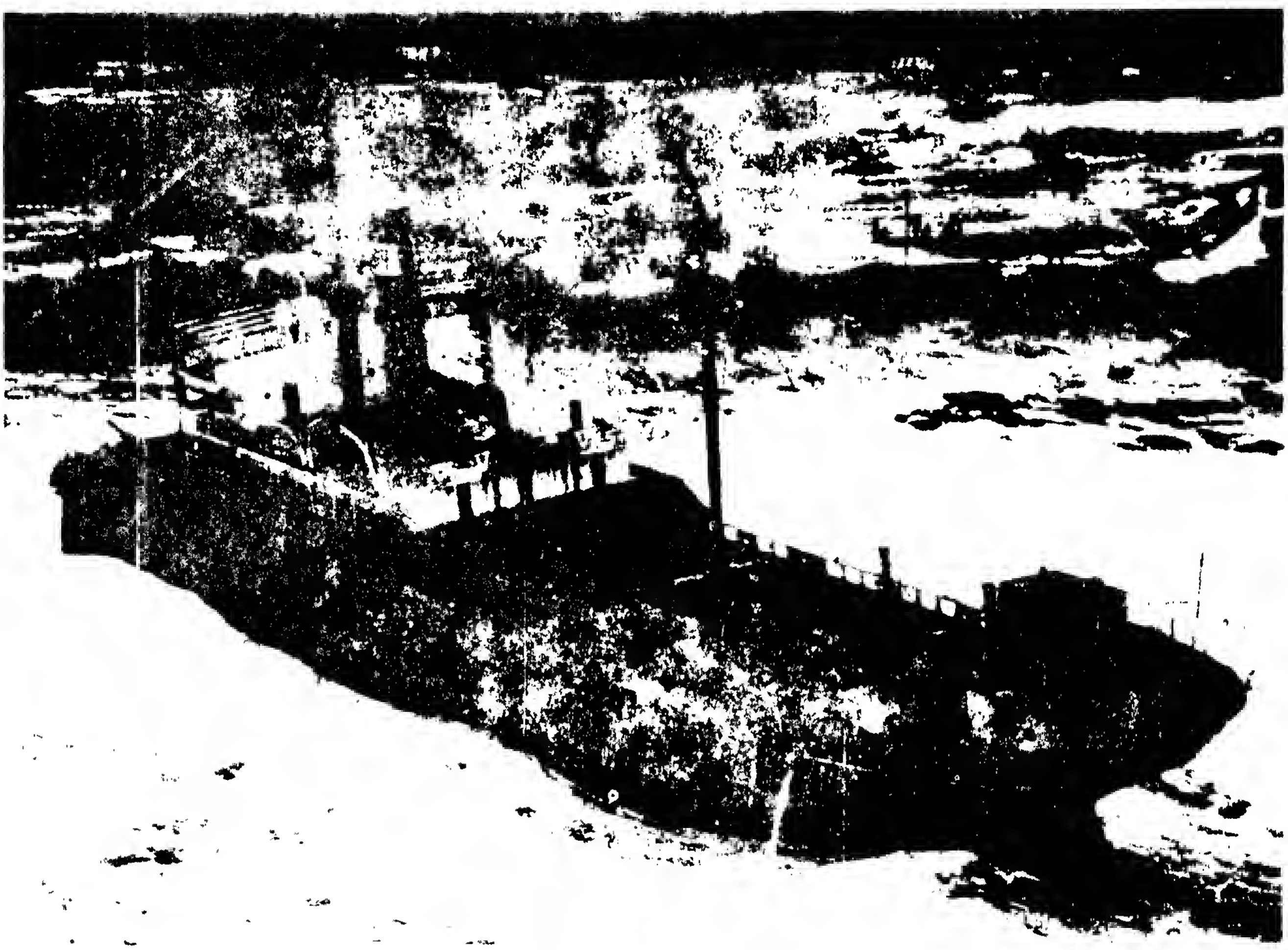
67 P. P. Puzak, A. J. Babecki, and W. S. Pellini, Correlations of Brittle-Fracture Service with Laboratory Notch-Ductility Tests, Welding J., 37 (9): 391S-407S (September 1958).

Structural Failure of a Riveted Ship

The *Oakey L. Alexander* was carrying a load of coal from Norfolk, Va., to Portland, Maine. A severe storm lashed the Atlantic coast. The heavy seas caused distress to shipping and was too much for the 31-year-old ship. Two huge waves boarded the ship from the starboard quarter, washed overboard the port lifeboat, damaged the starboard lifeboat and the boat deck, besides bashing in the oak doors in the deck house. The load of the seas was too heavy. The bow broke off. Her captain grounded her on the rocky coast near Portland, Maine.

When the seas had calmed the ship was boarded to investigate the structural failure and compare it with structural failures of welded ships.

During the last 4 years, the problem of structural failures in welded merchant ships was the subject of an intensive investigation. Studies



Damaged freighter *Oakey L. Alexander* grounded at Cape Elizabeth, Maine.

were made of all phases of ship construction procedures and a thorough research program was carried out in an attempt to discover the basic cause of hull fractures.

Some of the more common questions that have been asked concern the difference in the relative performance of ships constructed by means of riveting or welding. There are some facts which throw light on this difference. The following data form the basis for a partial answer to the question: "Were similar difficulties experienced on riveted ships?" Structural failures are not unknown on riveted ships. Such famous ships as the *Leviathan* and *Majestic* cracked their main decks. In other cases, such as the *Oklahoma* and *Mielero*, the ships broke in two.

These cases are well known in marine circles but the numerous lesser fractures have gone unheralded and without record. Attempts to compile statistics based on such minor failures are thwarted by the lack of evidence. On the other hand, for the last 4 years, the structural-failure data on welded ships were kept in a single central record where they were tabulated and analyzed.

Starboard side looking forward at edge of curled-up deck plating. The cleavage fracture turns to shear in the vicinity of riveted seam and then back to cleavage beyond the seam.

During the last war, great numbers of nearly identical welded ships were constructed. Upon the basis of the service records of these similar structures, it was possible to prepare statistical studies. No similar volume of production of riveted ships ever took place. Even the ship-building program of Hog Island ships during World War I did not approach the production volume of Liberty ships and T-2 tankers during World War II. The large volume of production of welded ships and the broad survey of structural failures made during the last 4 years permitted a complete statistical analysis which was presented in the final report of the board to investigate the design and methods of construction of welded steel merchant vessels. Since similar records are not available with respect to riveted ships, the exact answer to the question of their relative performance will never be obtained.

Even before the *Oakey L. Alexander* broke in two, many people asked the question: "Were the structural failures of welded ships similar to those which occurred on riveted ships?" This question could not be answered for a long time because few facts were available for detail study or ready comparison.

The many investigations made on the structural failures of welded ships, broadened the knowledge of fracture characteristics of steel plates and of typically sensitive design features.

When the *Oakey L. Alexander* was boarded by structural experts, they applied the knowledge gained in 4 years of investigation and analysis of welded-ship structural failures. It was possible to survey this ship and compare the findings with the results of investigations of other ship failures. All the phases of the hull structural failure were carefully photographed, sketched, and measured. Various samples were removed and forwarded to the National Bureau of Standards for analysis. The final results of this survey will not be available for many months. The general observations made at the survey are very interesting and will in part answer the question quoted above.

The fractures were found to have started at the square corners of the hatches. In addition to the main fractures which broke the ship in two, two minor fractures were found at other hatch corners. These fractures, however, did not continue to spread.

The fracture of the plates was classified as "cleavage." The term cleavage is applied to a crystalline-appearing fracture which is square to the plate surface, exhibits little reduction in thickness or stretching of the ma-

Coaming of No. 4 hatch, starboard side looking outboard, showing the main deck curled up under the force of damage.

terial, and which usually has a discernible herringbone pattern pointing toward the starting point of the fracture.

In the way of the starboard deck seam and at certain other locations, it was found that the mode of separation changed from "cleavage" to "shear." A "shear" fracture is silky in appearance, occurs at 45° to the plate surface and is usually accompanied by considerable stretching of the plate. Such fractures were rarely found in the welded ship failures except where a fracture terminated. In this ship, it would appear that the fractures had run from the hatch corners to the riveted seams where a slight pause took place and the fracture changed to "shear." The pause was only temporary, however, as the load on the riveted seams was more than the plating could stand and ultimate failure of the entire hull resulted.

All characteristics of the welded steel ship failures were present. Certainly, it can be said that the structural failures of the two types of ship are essentially the same. The presence of the riveted seams undoubtedly arrested the spread of cracks in numerous cases of riveted ship failures. It is likely that this resistance to the continuation of cracks is the one real difference between the two types of structures. Cracking of one or two plates is not spectacular and would not be expected to attract broad interest. Certainly, the modes of fracture are not fundamentally different and it is likely that the more illusive features attributed to the riveted structure are due to nothing more than lack of detailed facts regarding structural failures in the riveted hulls.

Fig. 1 — Fragment of a Fractured Drum. Note shiny, faceted appearance, sometimes called the chevron pattern. Apices of herringbone markings point to the origin of failure

Brittle Failure of Steel Structures —a Brief History

*By M. E. SHANK**

Although 250 welded ships have been disabled since 1940 by brittle cracking, such failures began as soon as steel plate became available for structural use and include storage tanks, bridges, booms and long pipe lines.

During World War II the problem of brittle failure received sudden prominence with the breaking up at sea and at dockside of welded steel merchant vessels, especially Liberty Ships and T-2 tankers. For this reason, in the minds of some persons, the problem of brittle failure is associated mainly with ships. However, a study of other steel plate structures shows that brittle failure is a general engineering problem, not confined to ships nor any other single category.

Neither is the problem a new one. In 1856, Bessemer announced his process of steelmaking, and shortly thereafter steel became available in comparatively large quantities. A few years later (1861), openhearth steel became available. Formerly, steel had been made by carburizing wrought iron; it was scarce and expensive; therefore, it was limited to such uses as cutlery and

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This paper is based, in part, on a report to the Committee on Ship Structural Design of the National Academy of Sciences, National Research Council. The Committee on Ship Structural Design is advisory to the interagency Ship Structure Committee which supported this investigation as part of its research program.

The complete report, "A Critical Survey of Brittle Failure in Carbon Plate Steel Structures Other Than Ships", was published as Report SSC 65 by the Ship Structure Committee, U. S. Coast Guard Headquarters, Washington 25, D. C. It is also available as Bulletin No. 17 of the Welding Research Council.

The opinions expressed in this article are those of the author and do not necessarily represent the views of the Committee on Ship Structural Design or the Ship Structure Committee.

Fig. 2 – Hassell Bridge in Belgium. Note extreme brittleness of breaks (Metal Progress, *May 1939, P. 492)*

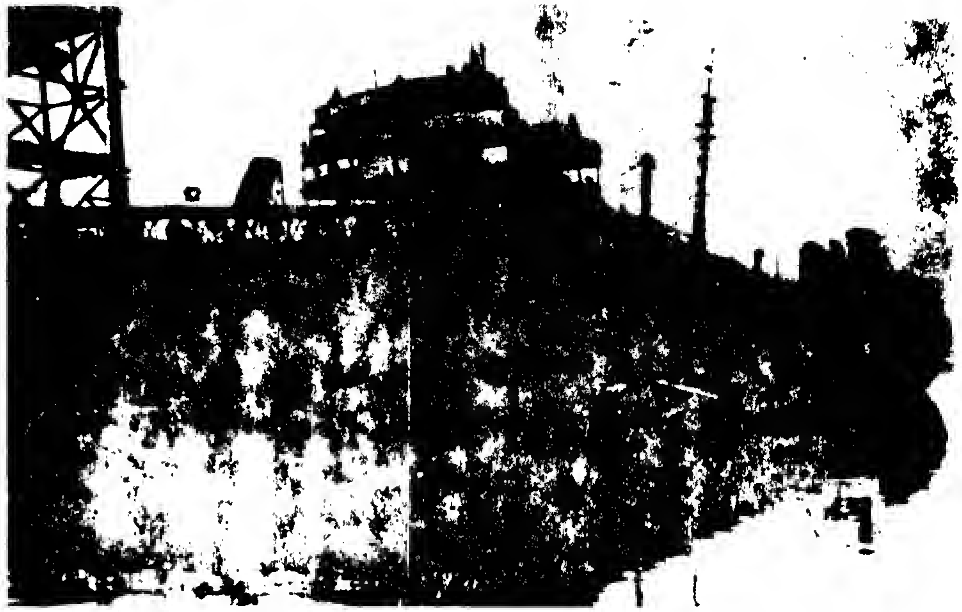


Fig. 3 – T-2 Tanker Which Broke in Half at Dockside

springs. Wrought iron and cast iron were the structural materials. In Great Britain, Board of Trade regulations prohibited the use of steel in construction, and their revision in 1877 provided a great stimulus to the steel industry in that country. Thus, during the period of 1860 to 1890, both in Europe and the United States, wrought iron was gradually being supplanted as a structural metal by steel. Reluctance by engineers to discard the old reliable wrought iron caused the change to come about slowly, but in the long run, the cheapness, greater availability, and superior strength of steel won out. As more steel came into use, troubles with brittle failure began to appear.

In the *Journal* of the Iron and Steel Institute for 1879 appears a paper by Nathaniel Barnaby on "The Use of Steel in Naval Construction". Mr. Barnaby deplores: "Recent cases have occurred of fracture in bessemer bars . . . from some trifling blow or strain . . . they nearly all took place during the late severe weather at Chatham."

In the ensuing discussion of the paper, Mr. Barnaby was roundly denounced by the assemblage. However, in that same meeting one Mr. Kirk complains of the cracking of steel in a mysterious manner. In particular, he cites a steel plate which "when cold, on being thrown down, split right up. Pieces cut from each side of the split stood all the Admiralty tests. Now given a material capable of standing without breaking an extension of 20% he wanted to know . . . how a plate . . . could split with a very slight extension . . . not to the extent of 1%."

Mr. Kirk thereupon asked the steelmakers for a remedy to this problem, and, if a remedy was not available, at least a rational explanation. His question was totally ignored. Today the problem is yet with us, and modern engineers and metallurgists are still striving to satisfy Mr. Kirk's request of 75 years ago.

It might be well to summarize briefly the manifestations of brittle fracture occurring in carbon steel plate.

Three conditions may combine to bring about such failures: First is low temperature – say +40° F., to –40° F., such as exists in the ambient atmosphere. Second is the presence of a notch (introducing triaxial stress); any defect such as a welding crack or a void, or a crack left by a punching or shearing operation can serve as a notch which will initiate brittle failure, and so it is sometimes called "notch brittleness". The third factor is high strain rate, but such impact loading is not necessary for brittle failures; as will be shown, many have been initiated under what appear to be completely static conditions.

When brittle failure occurs, it may be recognized by several earmarks. Among these are the speed at which fracture occurs (approaching several thousand feet per second), almost complete lack of ductility, negligible energy absorption, and a "brittle" or faceted appearance of the

fractured surface. Moreover, the fractured surface often has a characteristic "chevron" or "herringbone" appearance, the apices of the herringbones pointing to the origin of the fracture, an extreme example of which is shown in Fig. 1. Finally, when steel plate taken from a structure which failed in a completely brittle manner is tested in an ordinary tension test, it manifests a high degree of ductility and strength! It is this last characteristic which was so baffling to engineers.

Failures of Riveted Structures

Steel plate was customarily joined by rivets, of course, up to about 30 years ago. The earliest structural brittle failure on record, apparently, is a riveted water standpipe at Gravesend, Long Island, in 1886. It was an ambitious design, 250 ft. high, 16 ft. in diameter up to a height of 59 ft., decreasing conically in a length of 25 ft. to an 8-ft. diameter, which was retained to the top. The whole was steadied by guy wires. Plates in two sizes, 5x7 ft., and 5x9 ft., were employed with thicknesses varying from 1 in. at the bottom to ¼ in. at the top. All joints were triple riveted. Failure occurred during the hydrostatic acceptance test. Water had been pumped to a height of 227 ft. when there was a sharp rending sound; a vertical crack appeared in the bottom, running up about 20 ft. The whole tower then collapsed. An eye-witness noted that the workmanship seemed to be good, that some of the upper plates were tough and ductile, having actually rolled up, while others in the bottom of the tower were brittle with glass-like fractures. He concluded that only a brittle material could have wrought the destruction that occurred, and that it seemed as if all this defective plate had been concentrated in the lower part of the tower.

From 1898 up through 1933 engineering publications contain occasional accounts of brittle failures of riveted water tanks, gas holders, oil storage tanks, and ships. However, since 1900 over a dozen riveted merchant ships have broken in two or are listed as missing. It may be significant that most of these vessels were of the tanker type (the same category that has given the most trouble in welded ships) but such famous passenger liners as the Leviathan and the Majestic experienced cracks in their upper strength decks. These cracks started in square openings and sometimes extended to the shell — some even extended down the shell. In at least one case a loud report accompanied the forma-

Fig. 4 — Failed Spherical Pressure Vessel at Morgantown, W. Va., Showing Long Brittle Tear

Fig. 5 — Failed Power Shovel Boom. The end of the boom (pressed plate) has broken off

tion of a crack, indicating brittle fracture. The Europa had similar cracks.

The most famous brittle failure of a riveted structure was a molasses tank in Boston. One January day in 1919, when the tank contained 2,300,000 gal. of molasses, it burst open. Twelve persons were drowned in molasses or died of injuries; 40 others were injured. Houses in the path of the flood were damaged and a portion of the Boston Elevated Railway knocked over. An extensive lawsuit followed, and many well-known engineers and scientists were called to testify. Much conflicting testimony was presented as to the cause, and it was here that the significance of the chevron pattern in a service failure (see Fig. 1) was recognized.

Finally after years of testimony, the court-appointed auditor decided that the tank failed by overstress. In comment he said: ". . . Amid this swirl of polemical scientific waters it is not strange that the auditor has at times felt that the only rock to which he could safely cling was the obvious fact that at least one-half of the scientists must be wrong. . . ". This statement fairly well summarized the engineering knowledge (or lack of it) concerning notch-brittle behavior.

Failures of Welded Structures

Bridges—Just prior to World War II, about 50 bridges of a type known as a Vierendeel truss were built across the Albert Canal in Belgium. They possessed straight lower chords and curved upper chords, joined by verticals. There were no diagonals, yet the structure was a very rigid one. Some of these bridges were built of welded or rolled I-beam and plate, others entirely of plate. The span and detail were varied to suit the location. In March 1938 when the weather was quite cold the bridge at Hasselt, with a span of 245 ft., collapsed into the canal (Fig. 2). Eyewitnesses heard a sound like a shot and saw a crack open in the lower chord. This left the top chord acting as an arch. Six minutes later the bridge broke into three pieces, and fell into the canal. All the fractures were brittle, some through welds, others in solid plate away from the welds. The bridge was lightly loaded at the time. Within two years, two similar bridges failed in the same way.

These failures set off a great flurry in engineering circles. Numerous references to them, and to the supposed cause, were made by foreign correspondents to *Metal Progress*. The Belgium-Luxembourg steel industry claimed that the quality of the steel was above reproach, and the failure of the Hasselt bridge was due to poor welds. Representatives of the welding industry had also visited the site and satisfied themselves that the failure was not due to the weakness or imperfection of the welded joints.

Both judgments were premature. Several years later a thorough investigation was undertaken by two Germans, H. Busch and W. Reuleke. They reported that most failures were initiated at welds, and that many welds were defective. They found that on Charpy notch-impact tests practically all specimens were brittle (at least in part) at the cold temperature which existed at the time of failure. Their conclusions stated that the accident was caused by *(a)* multiaxial restraint and residual stress, *(b)* low ambient temperature, *(c)* low notch-impact characteristics of the steel. They seriously questioned whether nonkilled bessemer steel should be used in thick plate, despite good static-tension properties, since its notch-impact is low.

The Vierendeel bridge failures were a prelude to the brittle ship failures which occurred in World War II. Between 1942 and 1952 about 250 welded ships suffered one or more brittle fractures of such severity that the vessels were lost or were in a dangerous condition. Nineteen of these 250 ships broke completely in two or were abandoned after their backs were broken; 11 were tankers, 7 were Liberty Ships for dry cargo. In the same 10-year period, 1200 welded ships suffered brittle cracks, generally less than 10 ft. in length, which did not disable the ships but were potentially dangerous. The foregoing figures are for ships over 350 ft. long; very few failures have occurred in smaller vessels.

Ships—The first welded ship failure was that of a T-2 tanker in January 1943. While the vessel was sitting quietly at her fitting-out pier in Portland, Ore., the deck and sides fractured amidship with a report heard for at least a mile. The vessel, held together only by its bottom plating, jack-knifed so the center rose out of the water. See Fig. 3.

In Liberty Ships, the majority of the failures started at square hatch corners and square cut-outs in the top of the "sheer strake" — that is, the highest strip of shell plating. The frequency of serious failures was reduced after structural details, such as hatch corners, were redesigned. In addition, riveted straps or crack arresters — similar to butt straps in riveted plate work — were installed in the deck and at the gunwales, and all plate welds terminated in a slot behind these crack arresters.

In the T-2 tankers, most failures initiated in defects at butt welds in the hull. No simple remedial measures were possible, but finally four or more crack arresters were installed on these tankers, two on the deck and two in the bottom. It is to be noted, however, that crack arresters, while limiting the *extent* of cracks, do not *prevent* their occurrence, and so the frequency of serious fractures in T-2 tankers did not markedly diminish. A recent directive of the American Bureau of Shipping calls for installation of additional crack arresters in these ships, as well as strengthening the hull girder.

Pressure Vessels—Brittle failures of pressure vessels have occurred in recent years. One of these occurred in Schenectady, N. Y., in February 1943. The vessel was a spherical hydrogen tank of welded construction, 38.5 ft. in diameter, with 0.66-in. wall of semikilled plate. It had been in service three months. The design was in accordance with Paragraph U-69 of the A.S.M.E. Code for Unfired Pressure Vessels. The design called for a working pressure of 50 psi., a working stress of 11,000 psi., and a weld efficiency of 80%. In 1942 it had been tested at 62.5 psi. and showed no leaks. The manhole of the tank had been made in two subassemblies (bolt flange of neck in one, collar and sphere plate in the other) and had been field welded in place. All manhole plates were made of ¾-in. sheared cold rolled plate. The plates were dished cold, and in accordance with Paragraph U-69 of the code, not stress-relieved.

On the day of the fracture the ambient temperature had been below zero, had risen 27° F. in 7 hr., and was 10° F. when failure occurred. The internal pressure was about 50 psi. The sphere burst catastrophically into 20 fragments, with a total of 650 ft. of herringboned brittle tears. The tears were plotted on a model, with directions of herringbones marked by arrows. All herringbones led back to the manhole, which was the origin of fracture. The intensity of the failure was greatest in the manhole region.

The general quality of the welding was excellent. Only a few feet of fracture followed welded seams or the heat-affected zones alongside. Later examination of the relief valves showed them to be operating satisfactorily. Except in a minor way, fractures did not involve support-leg attachments where stresses were high. On good evidence the possibility of internal explosion was eliminated. The field assembly of the manhole neck required heavy welds of many passes, and old cracks were found, as well as many small

Fig. 6 — Failed Gas Line, 30 In. Diameter, Showing Sinusoidal Nature of Fracture. Note longitudinal welded seam, which appears to be intact. Presumably this failure occurred while installation was being tested. (Courtesy Lincoln Electric Co.)

cracks in the inner, sheared edge of the neck.

The investigators believed the causes to be:

1. High stresses at the manhole neck resulting from the presence of the hole in the sphere.
2. Residual stresses approaching the yield point in the manhole neck due to shrinkage of the heavy welds; there were several old radial cracks in this region.
3. The use of semikilled steel, which was brittle under the existing circumstances.
4. Probably thermal "shock" due to the rapid rise of temperature which increased the hydrogen pressure, or to thermal stress resulting from uneven heating by the sun's rays. The large amount of energy available from the compressed gas was sufficient to scatter the pieces without an explosion.

The investigators recommended that gas vessels should be tested at twice the working pressure with water, rather than 1¼ times the working pressure with gas, and that subassemblies (such as manholes and nozzles) should be built in the shop, stress-relieved, and Magnafluxed for cracks, and designed to avoid heavy, built-up weld deposits which cause high residual stress.

Other spherical pressure-vessel failures occurred in Pennsylvania in March 1943 during a test, and at Morgantown, W. Va. (Fig. 4) in January 1944, also on test. In Cleveland, extremely disastrous failures occurred in a cylindrical and in a spherical gas pressure vessel in October 1944. These two vessels, built of a 3½% nickel steel, had been used to store liquefied

natural gas at a pressure of 5 psi. gage and -260° F. Burning liquid got into the storm sewers and fire spread into several blocks of residences nearby. In the ensuing holocaust 128 persons were killed, and damage amounting to $6,800,000 resulted.*

Other Structures—Failure of power-shovel booms and dipper sticks (the member which carries the bucket) have been reported. Most of these occurred in cold weather, at -15 to -20° F. Figure 5 shows a power shovel on which the end of the boom has broken off. The material was a "Man-Ten" plate, containing 1.25 to 1.70% manganese, usually classified as a low-alloy steel.

Similarly, the brittle failures of oil-storage tanks, a smokestack, and a penstock have been reported. Three new oil-storage tanks broke up before they had ever been filled. The weld overfill on the seams inside the tank had been chipped flush during erection, leaving tiny notches. Following a sharp temperature drop, long cracks appeared across the welds, entering the plates on either side.

Pipe Lines—In the period since 1948 failures have occurred in high-pressure gas transmission pipe lines. Pipe for these cross-country lines is now usually produced according to an American Petroleum Institute standard, which specifies grades of strengths. Comparatively high values of carbon (0.34% max.) and manganese (1.30% max.) are allowed. In one method of manufacture the pipe is cold formed, seam-welded, and hydrostatically cold expanded, both to round it and to boost its yield strength up to the value specified. It is then hydrostatically tested. Raising of the yield by cold work has an important economic consequence. Inasmuch as a thinner pipe wall can thus be used, a considerable weight of steel can be eliminated. Large savings result.

Installation methods and allowable pressure in transmission lines are covered by an American Standards Association code (now being revised). Under this code it is permissible, in sparsely populated areas, to carry a pressure (approximately 800 psi.) which will stress the pipe to 72% of its yield strength. In more densely populated areas stresses from pressure are limited to about 50% of yield strength.

There is little published information concerning failures in gas-transmission-lines. One short article says they range from 180 to 3200 ft. in length. (The failures here described occurred on test, after installation.) The cause – presumably the initiating cause – is stated to be well known, namely, gouging or scratching of the plate in transit or installation. The failures always follow a sine wave pattern and look as though there had been an internal explosion. See Fig. 6.

In addition, a report of the Federal Power Commission lists a number of "splits" of pipe which occurred on test and in service. These splits were in the pipe itself, not in the weld. Details about these accidents are unobtainable – indeed, many of the data were probably lost in subsequent repair and replacement. It seems probable that some of these splits represented brittle breaks, but that others did not.

Because detailed technical information is lacking, definite statements about brittle pipe-line failures are difficult. However, some interesting speculations can be ventured. One speculation concerns field welding to join sections of pipe. With the upper limits of carbon and manganese contents allowed in the steel under A.P.I. Standard 5LX, trouble may be encountered in field welding of girth joints, since air hardening and subsequent cracking might occur in the heat-affected zone.

Another speculation concerns the rate of crack propagation in steel versus the rate of pressure released in natural gas (methane) following a pipe break. The gas pressure will be released by an elastic wave traveling at the speed of sound, approximately 1300 ft. per sec., and this rate will not be affected by pressure. Experimental values of 2750 to 6600 ft. per sec. have been measured in brittle fracture of steel in the laboratory. Thus it appears that the gas-discharge pressure wave will never catch up with the brittle crack; the tip of the crack is always traveling in a stressed area. This would account for the long breaks described. Testing of pipe lines with water might prevent such long breaks, inasmuch as the velocity of an elastic wave in water is about 4800 ft. per sec.

To determine this and other unknown factors the gas industry is sponsoring a considerable amount of research on the complex problem of brittle failure.

*This disaster was extensively studied, and the report of the Mayor's Commission is on file in the Cleveland Public Library. Reports of investigations sponsored by the East Ohio Gas Co. and by the U.S. Bureau of Mines are also available on request.

EDITOR'S FOOTNOTE – This brief article about the history of brittle fractures in notable structures will be followed by others discussing the factors of importance in such failures, the probable mechanisms of crack propagation, and the possible solutions.

HATCH CORNER DECK AND SIDE SHELL OF A SHELTERDECKER

1. General

Open shelter-decker, 9000 tons DW, built in 1948.

Length	=	152.46 m (500 ft 2 in)
Beam	=	19.50 m (64 ft)
Draught	=	8.13 m (26 ft 8 in)

All-welded ship-hull. Conventional erection (plate by plate).

No abnormal event was found in the past history of the structure.

Some deck plates of the same manufacture as those in this ship showed edge cracks: those plates were replaced during building.

2. Circumstances of Fracture

Wind and weather conditions: ambient temperature +6°C. Heavy weather with rough sea. Wind forces 8 - 9 B. North Sea 1956.

Estimated stresses at the time of fracture: about 900 kg/cm^2 at point of fracture start.

3. Details of Fracture

The fracture started in the deck at port forward hatch corner (or No. 4 - hatch).

This corner was well rounded (0.175 m); the hatch coaming (which penetrates the deck) was welded to the deck plating. The origin was the liaison weld of the coaming, under the deck, which was very badly welded because of the inaccessibility due to the presence of the longitudinal deck stringer (see figure).

A brittle fracture propagated through the deck to the port side shell and down the hull side (2½ strakes) and ended in a 17 mm plate with marked banded structure.

The appearance of the surface of the fracture was brittle.

4. Material in the Region of Fracture

4.1. PARENT PLATE

Ship steel according to the rules of the Classification Societies (1948).

Numbering and thickness of the plates:
(See Tables III, IV and V)

4.2. WELD METAL AND HEAT-AFFECTED ZONES

Normal acid manual welding electrodes of current type (1948) diameter 4mm. Seams in main deck automatically welded with covered electrode.

5. Fabrication Data

5.1. PRE-TREATMENT OF MATERIAL

No cold or hot forming of the steel before welding, no heat treatment before or after welding.

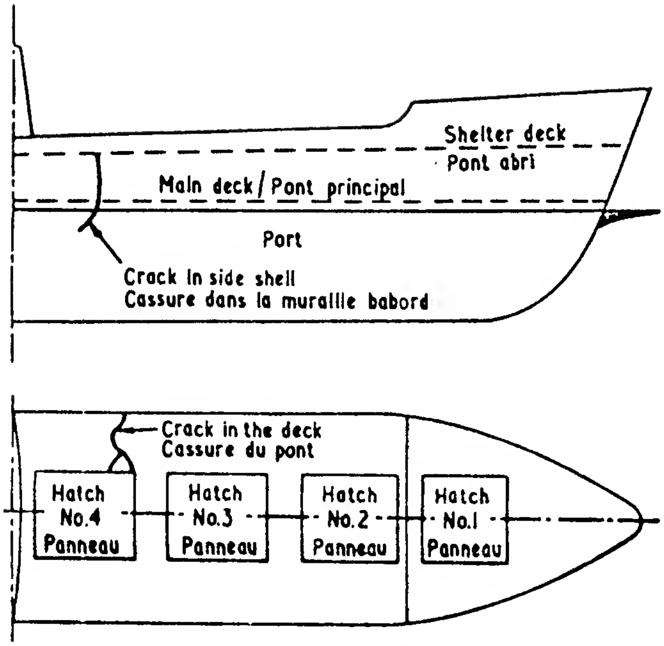
Document IIS/IIW-217-66 prepared by Commission IX "Behaviour of metals subjected to welding" of the IIW but not committing the IIW as a whole.

TABLE III - Numbering and thickness of the plates

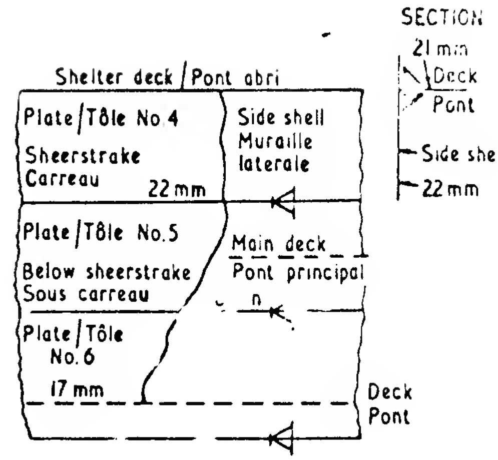
Plate Number	Location	Thickness	Remarks
1	Deck (at hatch) (origin)	22	Main Fracture
2	Deck	20	
3	Deck stringer plate	21	
4	Shell - Sheer strake	22	
5	Shell (Below No. 4)	17	
6	Shell (½ fractured end)	18	
7	Hatch coaming	12	Secondary fracture

TABLE IV - Check Analysis %

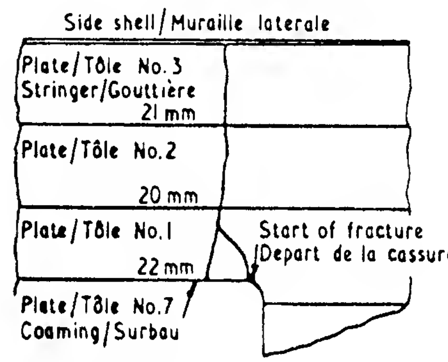
Plate Number	C	Si	Mn	P	S	Cr	Ni	Cu	N
1	0.26	0.01	0.61	0.020	0.039	0.02	0.02	0.04	0.007
2	0.18	0.01	0.33	0.034	0.036	0.02	0.11	0.18	0.007
3	0.25	0.03	0.40	0.032	0.034	0.02	0.17	0.18	0.006
4	0.22	0.01	0.37	0.042	0.034	0.03	0.14	0.18	
5	0.18	0.02	0.42	0.036	0.032	0.02	0.15	0.18	
6	0.20	0.01	0.42	0.032	0.057	0.03	0.03	0.18	
7	0.26	0.01	0.34	0.046	0.052	0.02	0.16	0.18	



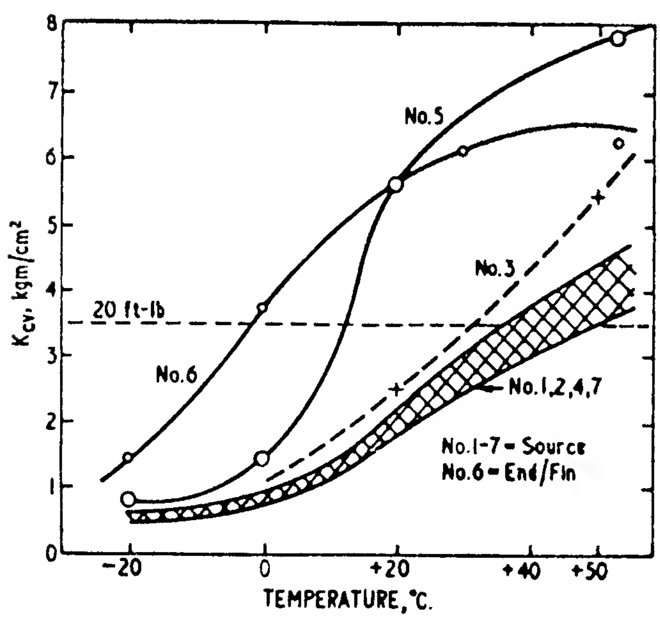
LOCATION OF THE CRACK
EMPLACEMENT DE LA CASSURE



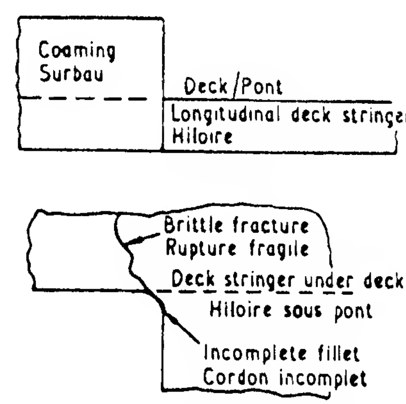
PATH OF THE CRACK (LOOKING PORT)
TRAJET DE LA CASSURE (VU DE L'AXE VERS BD)



DETAIL – ORIGIN OF THE CRACK



CHARPY V-NOTCH TRANSITION CURVES
COURBES DE TRANSITION DES EPROUVETTES
CHARPY A ENTAILLE EN V



HORIZONTAL VIEW / VUE HORIZONTALE

5.2. ASSEMBLY SEQUENCE

Two fillet welds, joining coaming and deck plating were concerned. They had been inspected visually.

5.3. WELDING PROCEDURE

The edge of the deck plate was oxygen cut and ground (square edge).

TABLE V - Mechanical Properties

Plate Number	T (*) or L	Yield point kg/mm^2	Tensile Strength kg/mm^2	Elongation % 200 mm	Mean Charpy V-notch Impact -20° C	Values (kgm/cm^2) ± 0° C	+ 20° C	- 52° C
1	T	24.8	47.0	24.5			2.4	
1	L	25.4	47.0	25.5	0.4	0.8	2.1	4.1
2	T	25.1	43.5	25.0			2.0	
2	L	28.8	45.3	24.0	0.5	0.7	1.9	4.6
3	T	25.8	47.0	24.5			2.8	
3	L	30.4	47.6	24.5	0.5	1.0	3.4	5.4
4	T	22.0	44.6	24.0			1.2	
4	L	23.8	45.6	30.0	0.4	0.6	2.3	3.8
5	T	25.1	43.2	32.5			4.1	
5	L	25.9	43.3	26.5	0.8	1.6	5.7	7.8
6	T	37.2	48.6	17.5			3.9	
6	L	33.6	48.9	20.5	1.4	3.7	6.1	6.1
7	T	29.9	49.1	18.5			1.5	
7	L	32.5	51.5	21.9	0.5	0.6	1.9	3.6

* Test in ship yard shows about 26 kg/mm^2 yield point.

Microstructure of plate number 1, where the fracture started: Grain size ASTM : 7 (ferritic). Widmanstätten: traces. Plate number 6, where the fracture stopped: Grain size ASTM : 8 and 9.

The fillets were welded manually; the seams in the main deck were automatically welded with covered wire.

The electrodes were of a normal "A" (acid) type - Diameter: 4 mm (neither preheat, nor postweld treatment).

6. Comments of the Reporting Organisation

The surfaces of the fracture undoubtedly indicated a brittle fracture pattern. The lower fillet weld between the hatch coaming and the deck was carried out in very bad conditions because of its almost inaccessible location under the deck at the hatch corner. It is possible that the first part of the crack path showed some signs of fatigue fracture.

But in plate 1 no signs of fatigue fracture were detected. This first crack obviously served as an initiating notch for the brittle fracture of plate 1, caused by hard service conditions at a temperature where the steel showed low impact values.

7. Conclusions

The main factors involved were:

(a) Defective welding of the fillets, between the hatch coaming and the deck, without sufficient inspection after welding.

(b) This local fault possibly caused fatigue fissuring, after 8 years service, in one of the fillet welds (below deck).

(c) The quality of the 22 mm deck plate (source plate) is now questionable, in the light of the present shipsteel standards, in spite of the regulation with which at the time (1946) it complied.

(d) A high level of bending stress in the hull (not abnormal) occurring under the transition temperature of the steel.

Two other points are worthy of interest:

(1) The electrodes used at this highly stressed part of the ship were of the acid type.

(2) The end of the crack in the side shell was in a 17 mm plate at 1.3 m over the neutral fibre of the hull. It is of interest to note that this steel had a high sulphur content (0.057), a banded structure, a finer grain and a lower conventional transition temperature. At the failure temperature, its energy level was higher than that of other plates (4.6 kgm/cm^2) and also its fibrosity (75%).